eRD14 – EIC PID consortium

- An integrated program for particle identification (PID) for a future Electron-Ion Collider (EIC) detector.

M. Alfred, B. Azmoun, F. Barbosa, W. Brooks, T. Cao, M. Chiu, E. Cisbani, M.Contalbrigo, S. Danagoulian, A. Datta, A. Deldotto, M. Demarteau, A. Denisov, J.M. Durham, A. Durum, R. Dzhygadlo, D. Fields, Y. Furletova, C. Gleason, M. Grosse-Perdekamp, J. Harris, M. Hattawy, X. He, H. van Hecke, T. Horn, J. Huang, C. Hyde, Y. Ilieva, G. Kalicy, A. Kebede, B. Kim, E. Kistenev, M. Liu, R. Majka, J. McKisson, R. Mendez, I. Mostafanezhad, P. Nadel-Turonski, K. Peters, R. Pisani, W. Roh, P. Rossi, M. Sarsour, C. Schwarz, J. Schwiening, C.L. da Silva, N. Smirnov, J. Stevens, A. Sukhanov, X. Sun, S. Syed, R. Towell, G. Varner, R. Wagner, C. Woody, C.-P. Wong, W. Xi, J. Xie, Z.W. Zhao, B. Zihlmann, C. Zorn.

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Generic Detector R&D for an Electron Ion Collider

Advisory Committee Meeting, BNL, July 11-12, 2019

Participating institutions

- Abilene Christian University (ACU)
- Argonne National Lab (ANL)
- Brookhaven National Lab (BNL)
- Catholic University of America (CUA)
- City College of New York CCNY)
- College of William & Mary (W&M)
- Duke University (Duke)
- Georgia State University (GSU)
- GSI Helmholtzzentrum für Schwerionenforschung, Germany (GSI)
- Howard University (HU)
- Institute for High Energy Physics, Protvino, Russia
- Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, Italy (INFN-Ferrara)
- Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy (INFN-Rome)
- Istituto Superiore di Sanità, Italy (ISS)
- Jefferson Lab (JLab)
- Los Alamos National Lab (LANL)
- North Carolina A&T State University (NCAT)
- Old Dominion University (ODU)
- Stony Brook University (SBU)
- Universidad Técnica Federico Santa María, Chile (UTFSM)
- University of Hawaii (UH)
- University of Illinois Urbana-Champaign (UIUC)
- University of New Mexico (UNM)
- University of South Carolina (USC)
- Yale University (Yale)

eRD14: an integrated program for PID at an EIC

1. A suite of detector systems covering the full angular- and momentum range required for an EIC detector

- Different technologies in different parts of the detector
- Focus on hadron ID with an electron ID capability

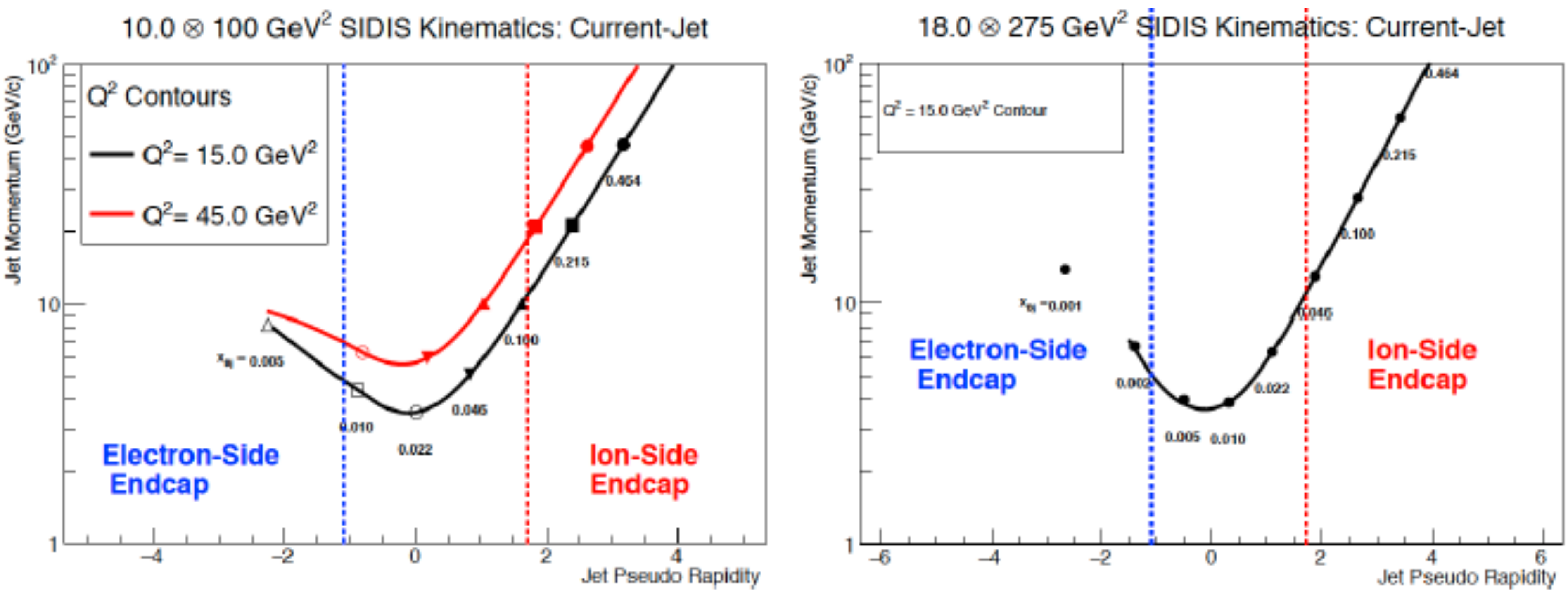
2. A cost-effective sensor and electronics solution

- Development and testing of photosensors (to satisfy EIC requirements)
- Development of readout electronics needed for prototyping

3. Consortium synergies (including reduction of overall R&D costs)

- Close collaboration within the consortium, with coordinated goals and timelines (*e.g.*, DIRC & LAPPD, mRICH & dRICH, etc).
- Strong synergies with non-EIC experiments and R&D programs (PANDA, CLAS12, GlueX, PHENIX, commercial LAPPDs) result in large savings.

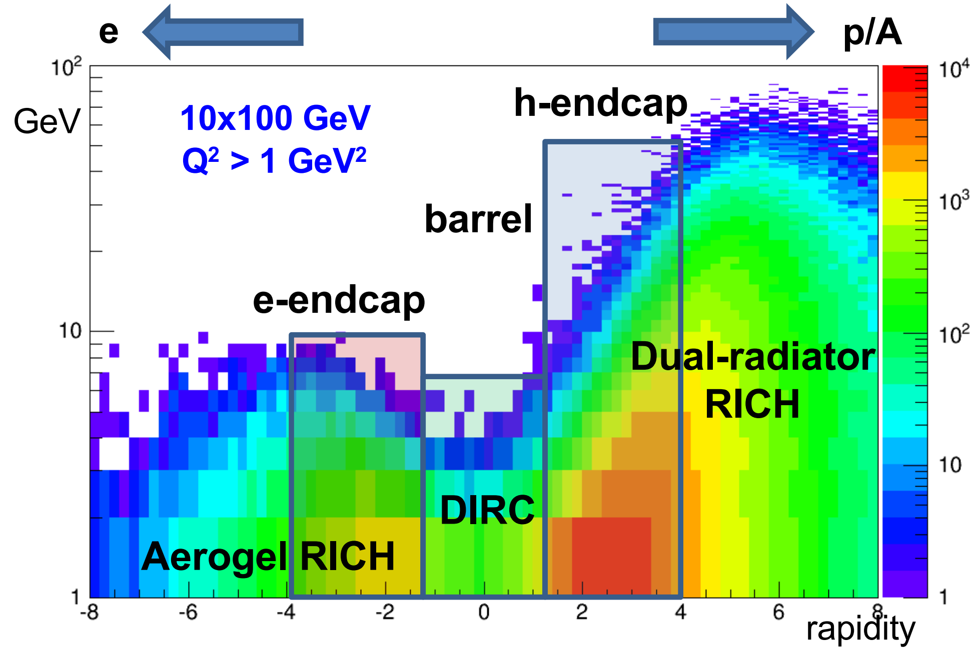
Hadron kinematics at an EIC

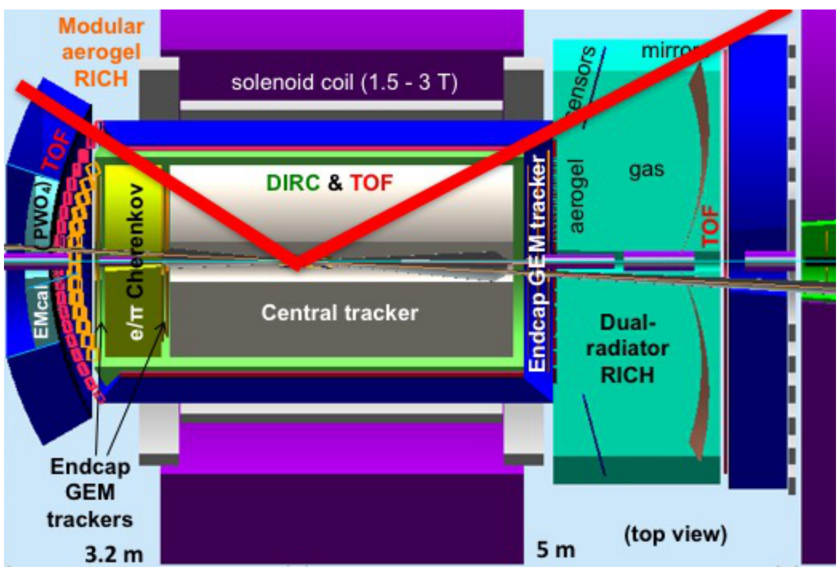


- The maximum hadron momentum in the endcaps is close to the electron and ion beam energies, respectively.

- The momentum coverage in the central barrel determines the kinematic reach, in particular in Q^2, which is important for QCD evolution, etc.
  - Weak dependence on beam energies

A PID solution for the EIC





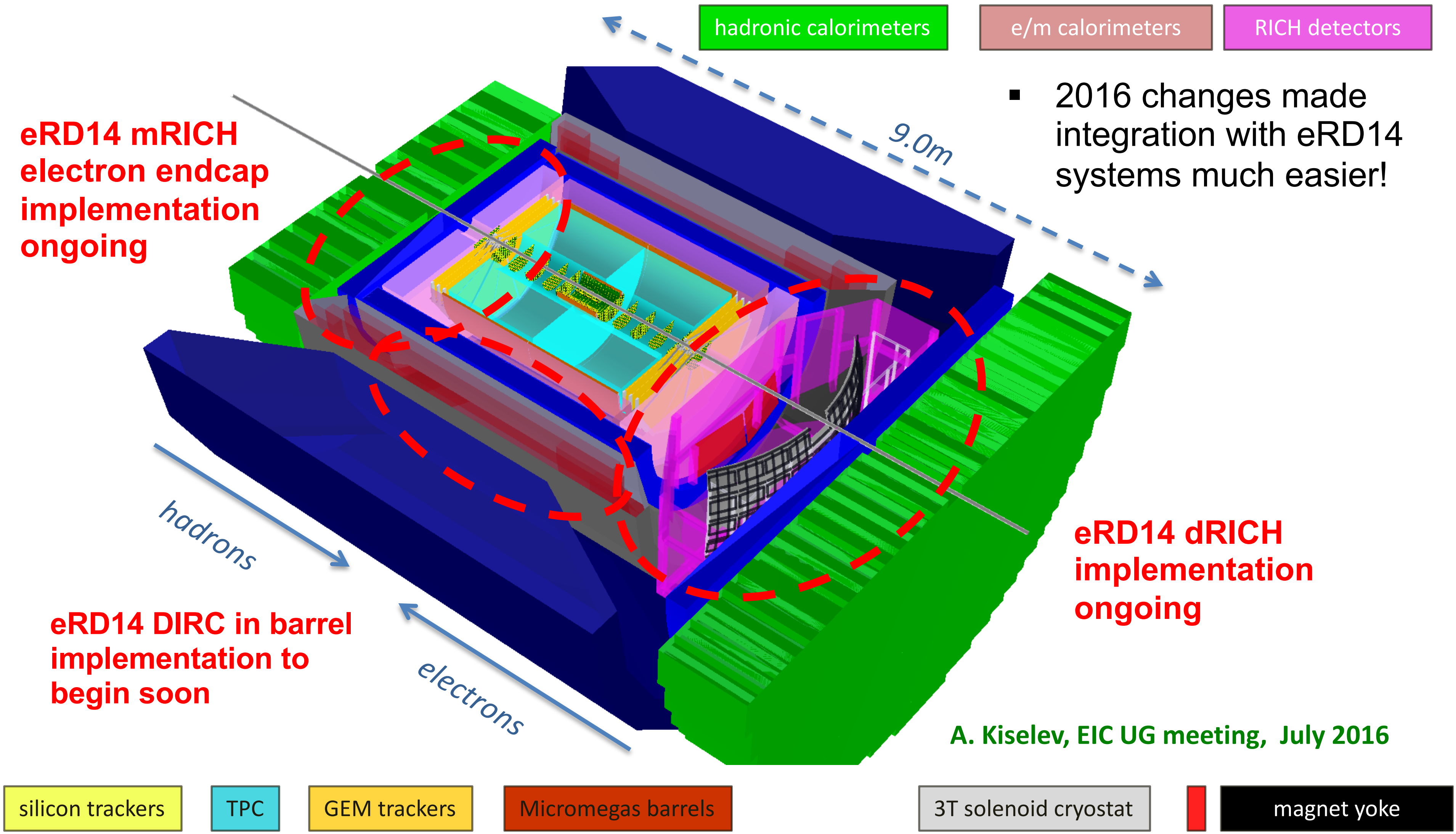
- **h-endcap**: A RICH with two radiators (gas + aerogel) is needed for
  π/K separation up to ~50 GeV/c
- **e-endcap**: A compact aerogel RICH which can be projective
  π/K separation up to ~10 GeV/c
- **barrel**: A high-performance DIRC provides a compact and cost-effective way to cover the area.
  π/K separation up to ~6-7 GeV/c
- **TOF and/or dE/dx in a TPC**: can cover lower momenta.
- **Photosensors and electronics**: need to match the requirements of the new generation devices being developed – both for the final system and during the R&D phase

PID in the EIC concept detectors and integration of eRD14 systems

BNL BeAST EIC detector

-3.5 < η < 3.5: Tracking & e/m Calorimetry (hermetic coverage)

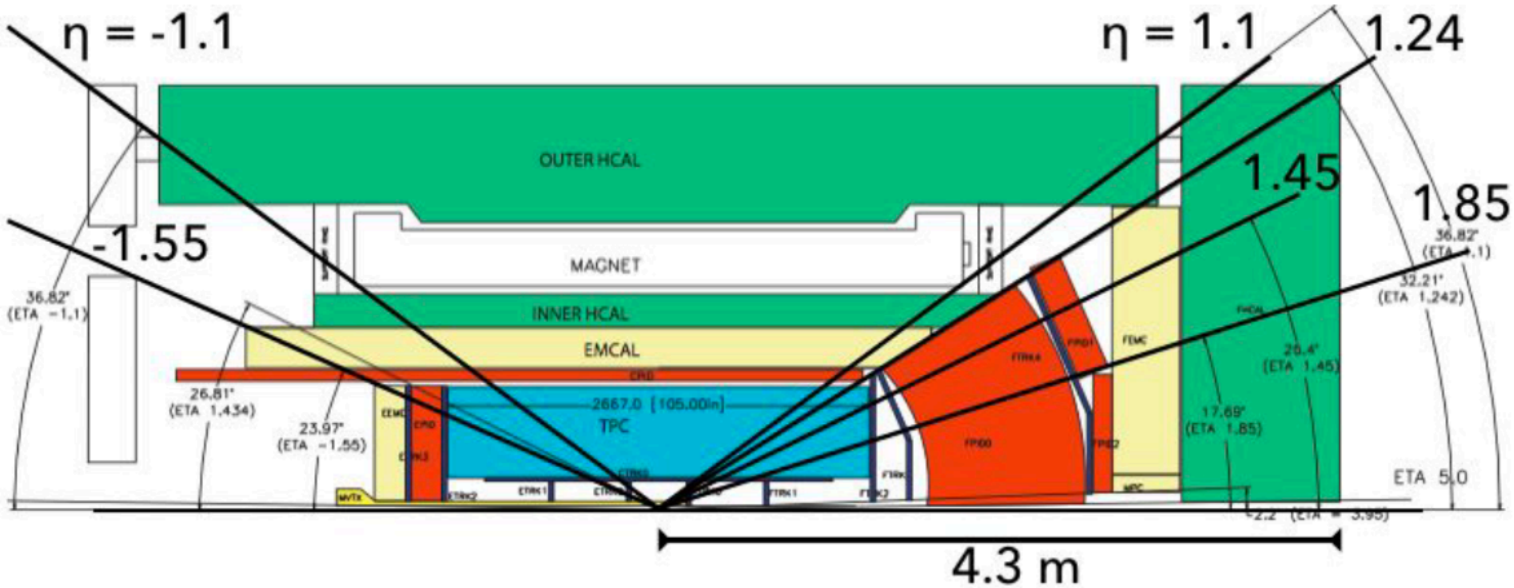
- 2016 changes made integration with eRD14 systems much easier!



A. Kiselev, EIC UG meeting, July 2016

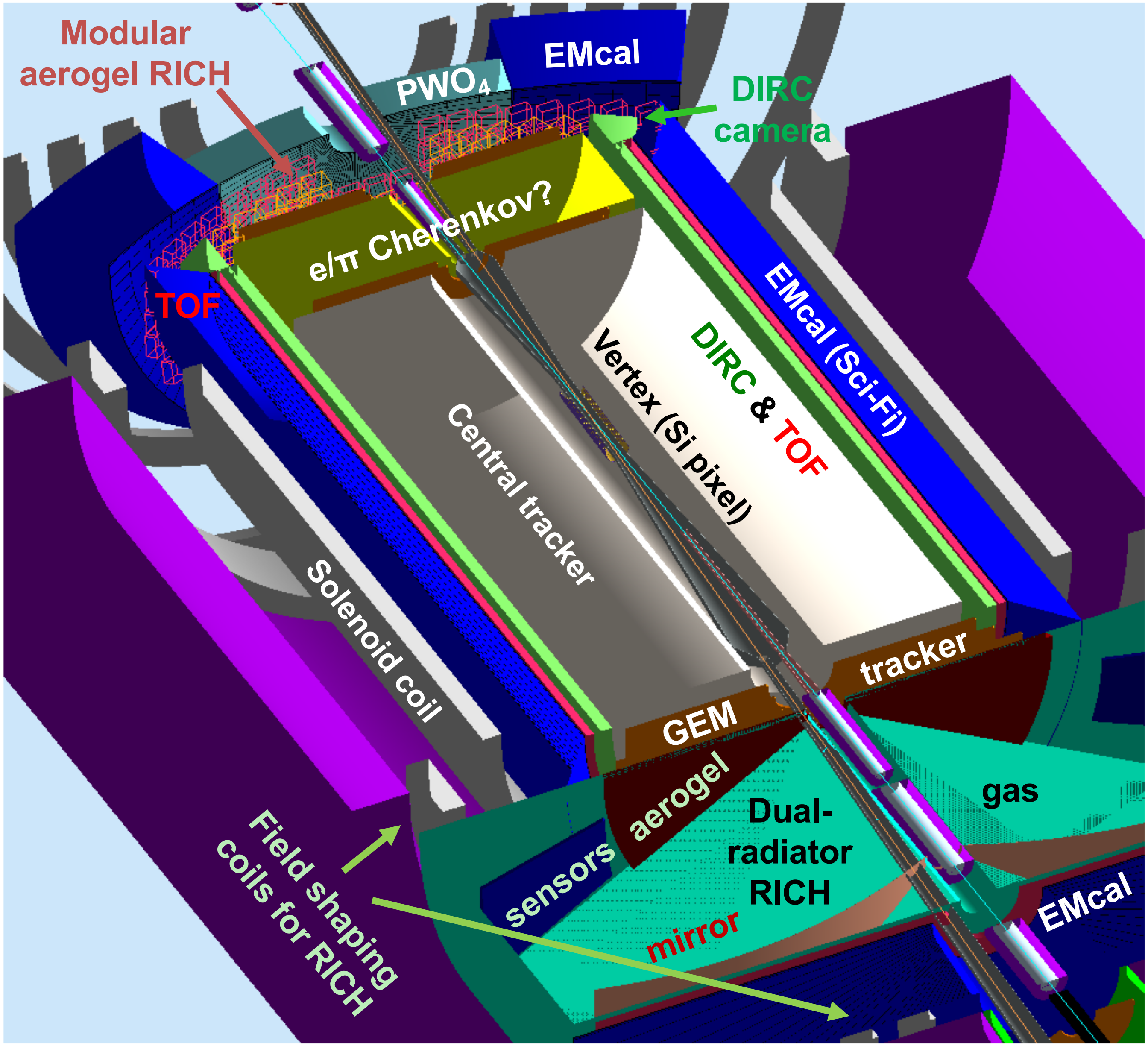
BNL ePHENIX EIC detector

- 2018 layout shown



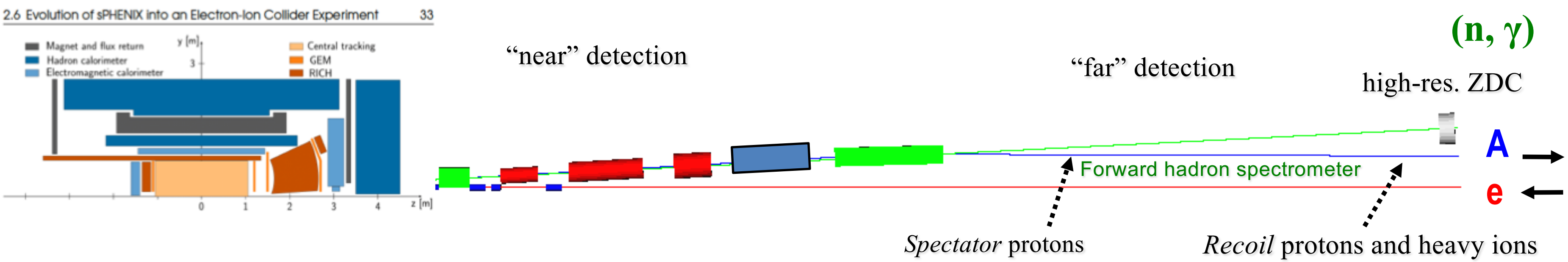
- The DIRC, mRICH, and TOF systems already part of the current concept. An implementation in Geant4 (Fun4All) is ongoing.
- In addition, either the eRD14 dRICH and eRD6 gas RICH could be used. The two options have been compared in a collaborative effort.

JLab EIC central detector showing PID integration



- All eRD14 systems (DIRC, mRICH, dRICH, and TOF) are part of the baseline JLab detector concept.

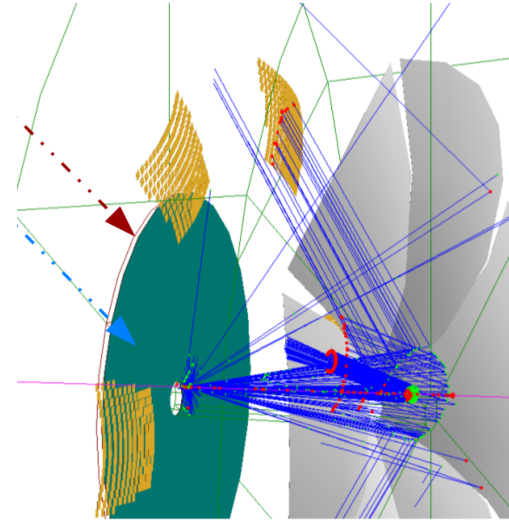
PID for ions at very forward angles



- Detection and identification of the target remnant(s) is an *essential* requirement for the EIC.
- Reactions on the proton are relatively straightforward. For light ions, the acceptance at low p_T becomes challenging (~A^2), while intact heavy ions cannot be detected directly (vetoing is needed).
- For light ions and ion fragments, PID also becomes important. To identify an ion we need to know both A/Z and have an independent measurement of Z or A. Since all fragments travel with the same velocity, TOF is not ideal.
- However, we can measure Z^2 through dE/dx or using a Cherenkov detector, which might be the only option for large Z. A pilot study for a "mini-DIRC" is proposed as a new, small R&D project this year.

Dual-radiator RICH (dRICH)

Dual Radiator: Aerogel (n~1.02), Gas (n_{C2F6} ~1.008)
6 Identical Open Sectors:
Large Focusing Mirror with R ~2.9 m
Optical sensor elements: ~4500 cm^2/sector



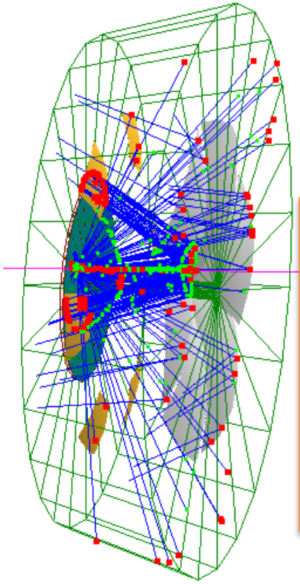
R&D Goals:

- Hadron identification (π/K/p, better than 3 sigma apart) with continuous coverage from 3 GeV/c up to ~50 GeV for π/K and ~15 GeV for e/π
- First such device developed for the endcap of a solenoidal detector

FY 20 Activities:

- Refinements on global particle ID reconstruction
- Apply Bayesian Optimization to improve dRICH performances
- Design dRICH prototype

Finalized IRT-Based **Global** Reconstruction



Inverse Ray-Tracing

Nt : tracks (+ background «dummy track»)

Nh : photon hits (photoelectrons)

Nr : radiators (aerogel and gas)

Np : potential particle types (e,pi,K,p)

~40% of PYTHIA events have multiple tracks in dRICH
~50% of them overlapping rings;
Simple track based IRT → π/K contamination>10%

Global naive «brute force» approach: explore all possible combinations of

Track ∈ Particle type hypothesis: Np^Nt

Photon hits ∈ (Track ⊗ Radiator + Background) : **(Nt*Nr+1)^Nh**

Each combination has an associated Likelihood; take the maximum

Our approach:

- Determine (by IRT) the potential emission angles corresponding to each photon hit
- Split the problem in two steps (for each event):
  1) Sequential hits association to tracks/radiators using a first likelihood L1 (combinations drop to **(Nt*Nr+1)*Nh**)
  2) Once all hits are associated, estimate a global Likelihood (L2) for each (track ∈ particle) combination; choose the combination with max L2

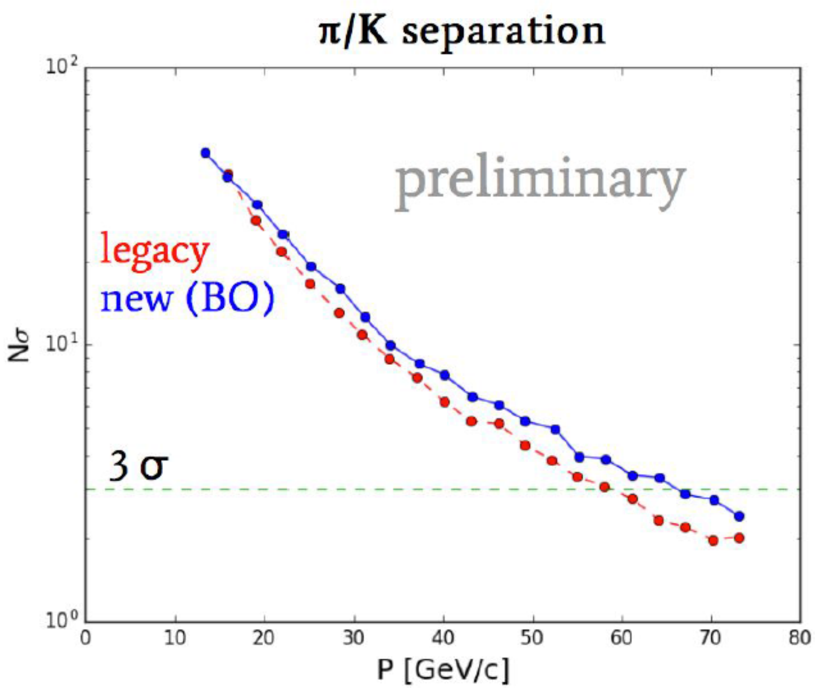
Example: event with 2 tracks and 15 hits

Brute Force: up to **~488 billion** combinations
Our approach: **1200** combinations

dRICH Performance Optimization using new tools

Goal: improve legacy (baseline) performance obtained in past year design

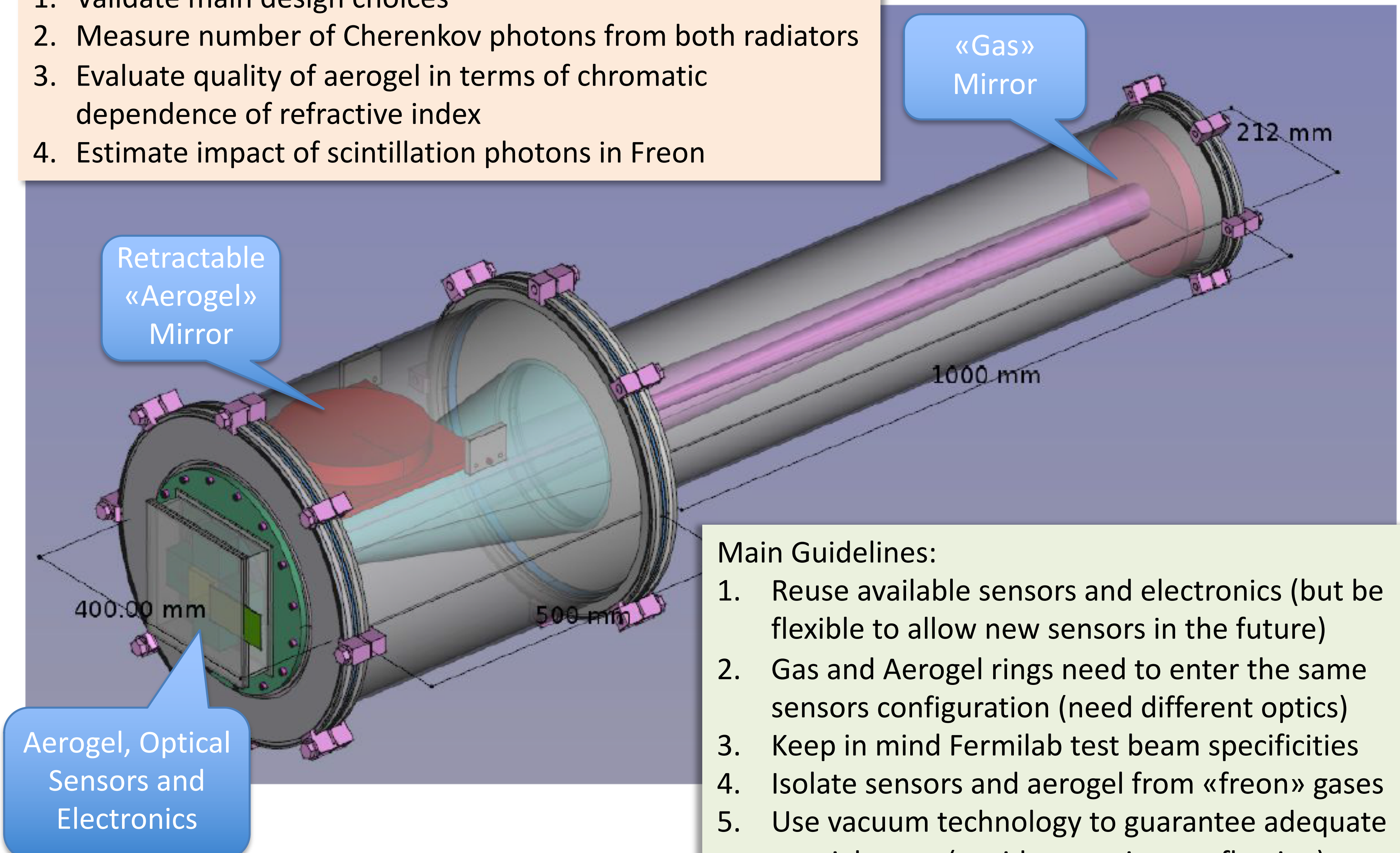
- Combine detailed Monte Carlo simulations with Bayesian Approach to maximize the Figure of Merit (pi - K Cherenkov angle separation in critical phase spaces regions)
- First implementation uses 7 independent parameters: aerogel refractive index, mirror radius and position, sensor position and orientation



- Number of free parameters can be extended (e.g. aerogel thickness, gas refractive index …)
- The optimization approach can be ported to any detector development where a detailed Monte Carlo exists
- Validated MonteCarlo is essential to get realistic results → prototype needed

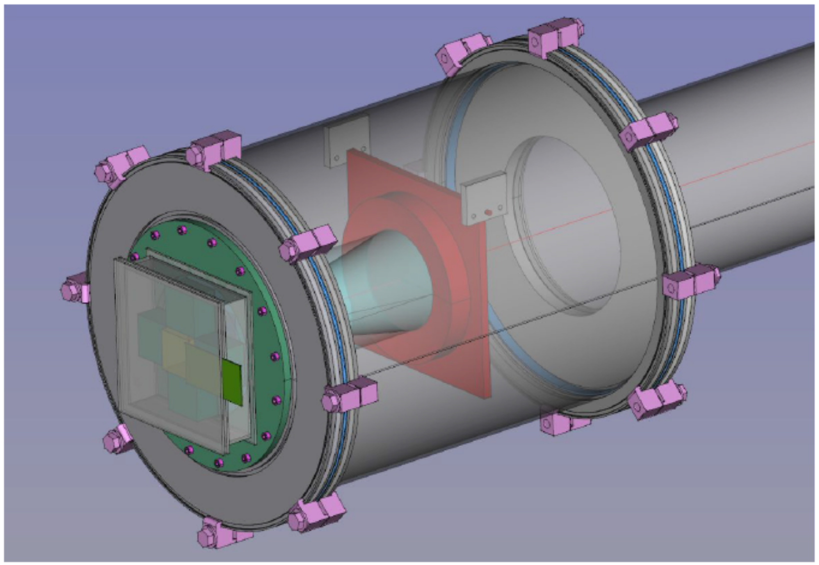
dRICH Prototype

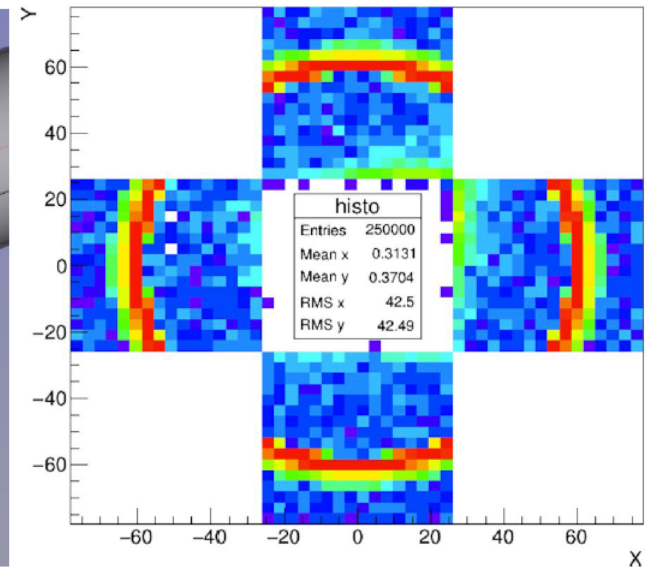
Goals:
1. Validate main design choices
2. Measure number of Cherenkov photons from both radiators
3. Evaluate quality of aerogel in terms of chromatic dependence of refractive index
4. Estimate impact of scintillation photons in Freon

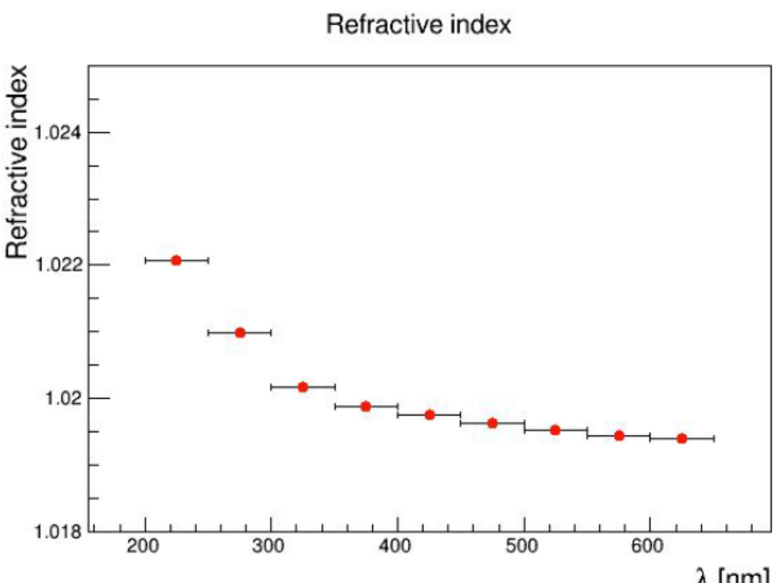


Main Guidelines:
1. Reuse available sensors and electronics (but be flexible to allow new sensors in the future)
2. Gas and Aerogel rings need to enter the same sensors configuration (need different optics)
3. Keep in mind Fermilab test beam specificities
4. Isolate sensors and aerogel from «freon» gases
5. Use vacuum technology to guarantee adequate gas tightness (avoid expensive gas flowing)

dRICH Prototype in aerogel mode

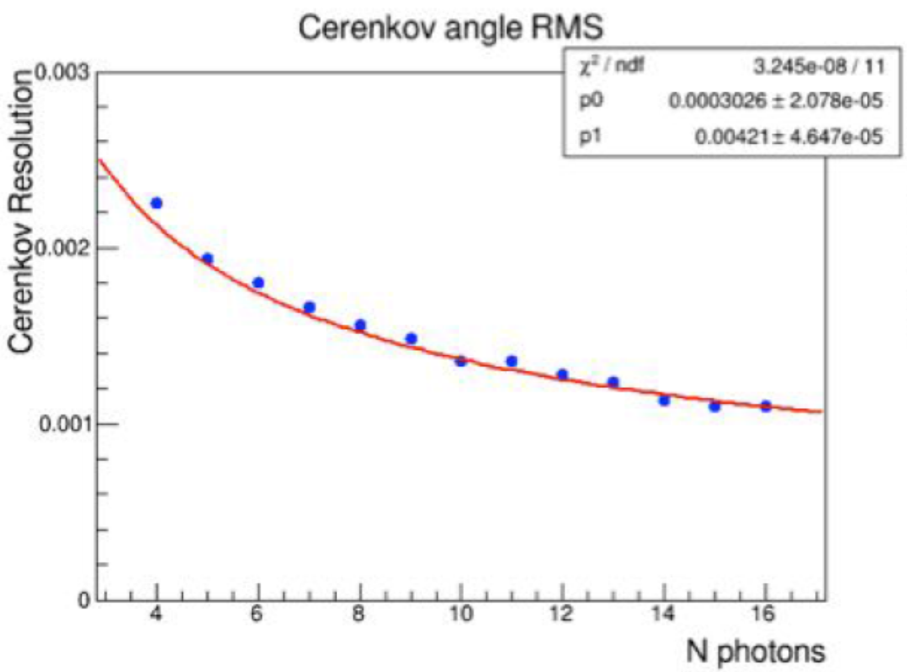


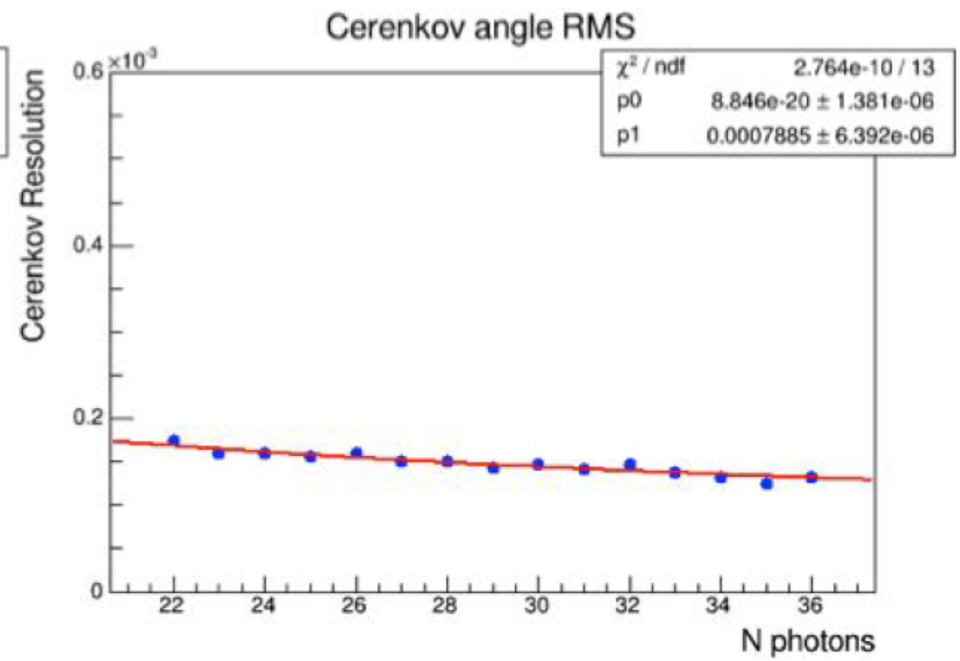




Example: measurement of the aerogel chromatic dispersion and UV filter optimization

dRICH Prototype - Expected Performance





1 p.e. Error (mrad)	Aerogel	C_2F_6 Gas
Chromatic error	3.2	0.51
Emission	0.5	0.5
Pixel	2.5	0.42

dRICH Status and Plans

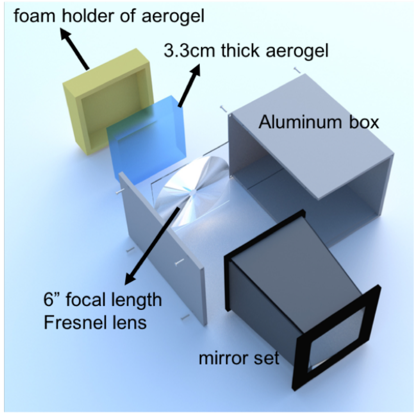
FY19 progress

- Application AI based methods (Bayesian approach) to the geometrical optimization
- Completion of the analysis of the event-based Cherenkov angle reconstruction algorithm
- Finalization of a realistic design of the dRICH prototype
- Extension of the dRICH simulations to the prototype case
- Start of prototype construction and procurement of its components
- Start of preparation of the aerogel/gas “long term” characterization

FY20 proposed activities

- Complete the prototype
- Perform a prototype test beam
- Validation of the Monte Carlo simulation based on GEMC
- Improve dRICH model based on the test results and re-estimate expected performances
- Continue long-term aerogel/gas characterization tests

Modular Aerogel RICH (mRICH)



Goal:

- Compact PID device with momentum coverage up to 10 GeV/c for π/K and e/π up to 2 GeV/c.
- First aerogel RICH with lens-based focusing (for performance and cost).

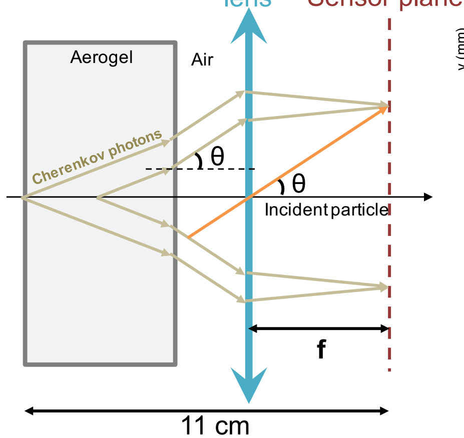
FY20 Activities:

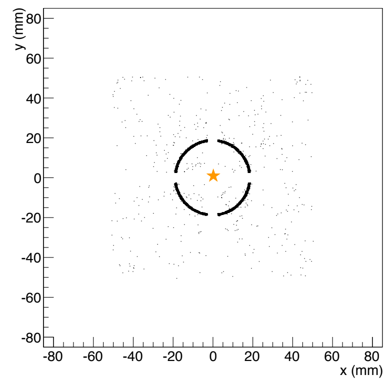
- Data analysis of the second mRICH beam test (ongoing effort).
- Study of radiation hardness of Fresnel lens.
- Simulation study of mRICH performance in the electron endcap of JLEIC and in the Forward sPHENIX experiments at BNL (ongoing effort).
- Organize a joint dRICH/mRICH beam test. Plan for an electron beam (~2 GeV/c) test.
- Optical characterization of Fresnel lens and aerogel block properties.

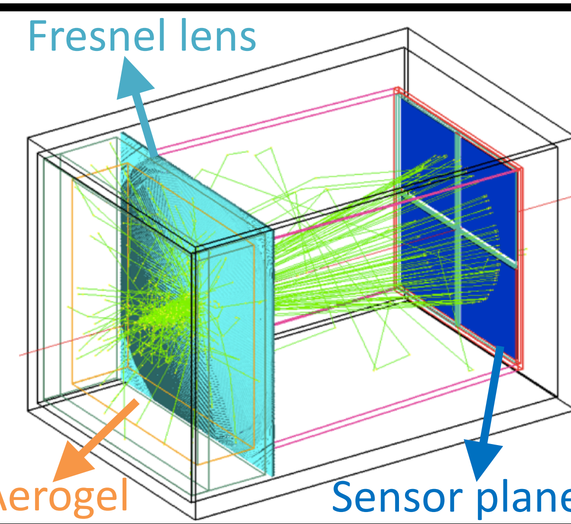
mRICH – lens-based focusing aerogel detector design

Smaller, but thinner ring improves PID performance and reduces length

Lens-Based mRICH Design

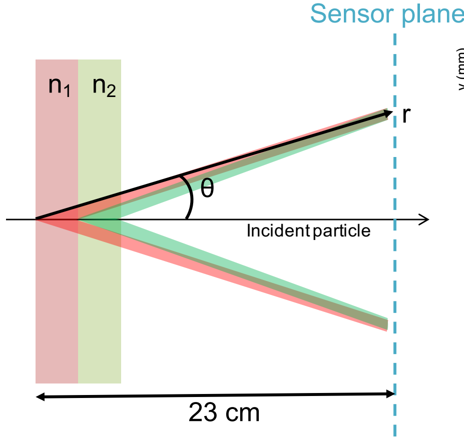


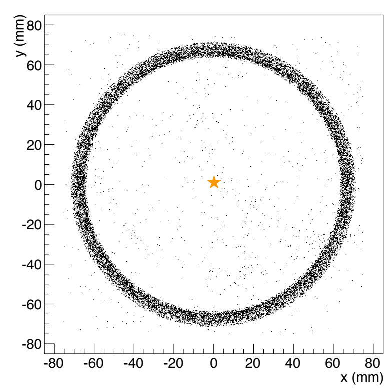




9 GeV/c pion beam launched at the center of xy plane in simulation

Two-Layer Proximity Focusing Design (BELLE-2 ARICH)



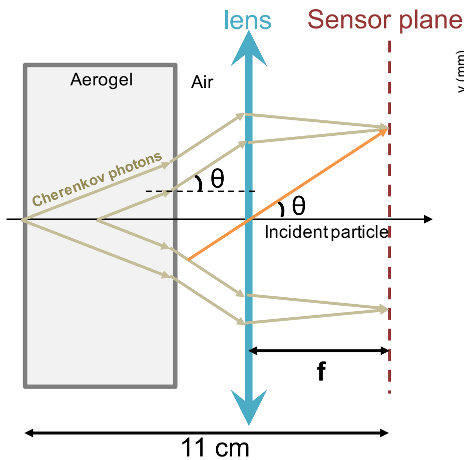


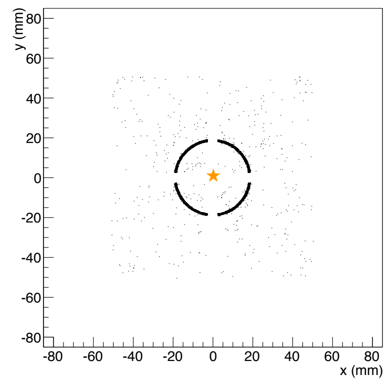
- EIC mRICH designed for K/pi ID up to 10 GeV/c
- BELLE-2 ARICH aims to separate pion and kaon up to 4 GeV/c

mRICH – lens-based focusing aerogel detector design

Smaller, but thinner ring improves PID performance and reduces length

Lens-Based mRICH Design

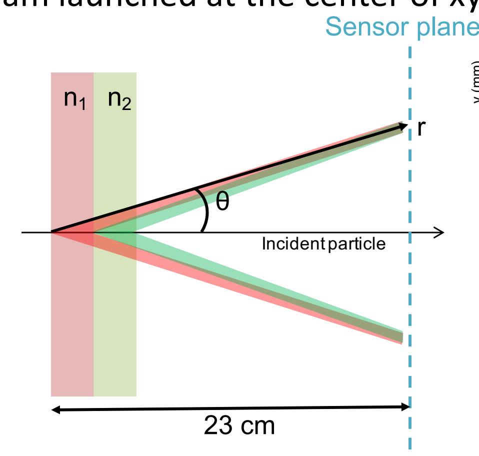


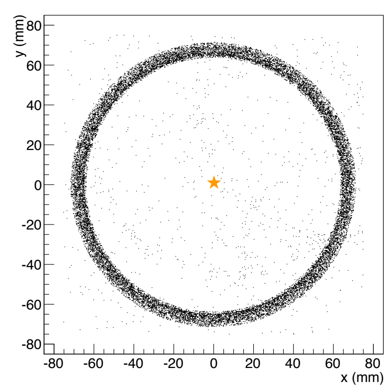


- 9 GeV/c pion beam launched at the center of xy plane in simulation
- **Smaller and thinner** ring image

9 GeV/c pion beam launched at the center of xy plane in simulation

Two-Layer Proximity Focusing Design (BELLE-2 ARICH)



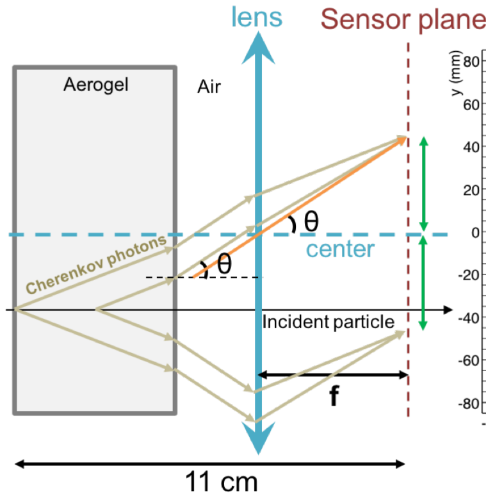


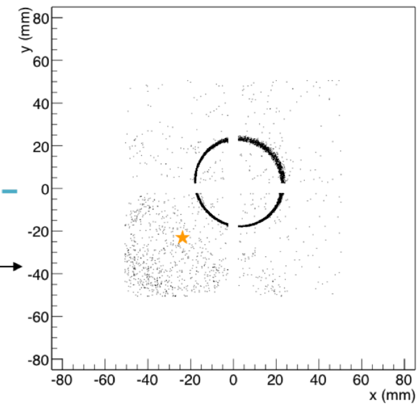
- EIC mRICH designed for K/pi ID up to 10 GeV/c
- BELLE-2 ARICH aims to separate pion and kaon up to 4 GeV/c

mRICH – lens-based focusing shifts image to center

Ring centering of lens-based optics reduces sensor area (main cost driver)

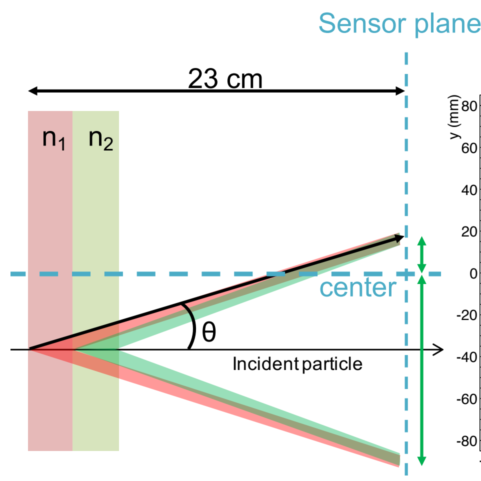
Lens-Based mRICH Design

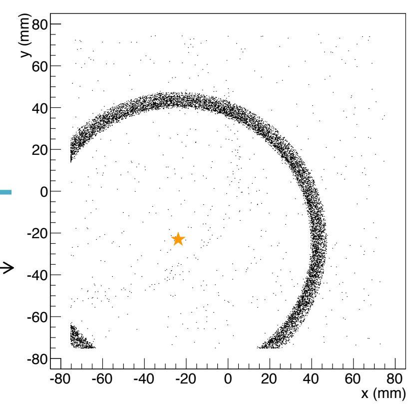




- 9 GeV/c pion beam incident at third quadrant (star) in simulation
- Ring image is **center** on the middle of the sensor plane

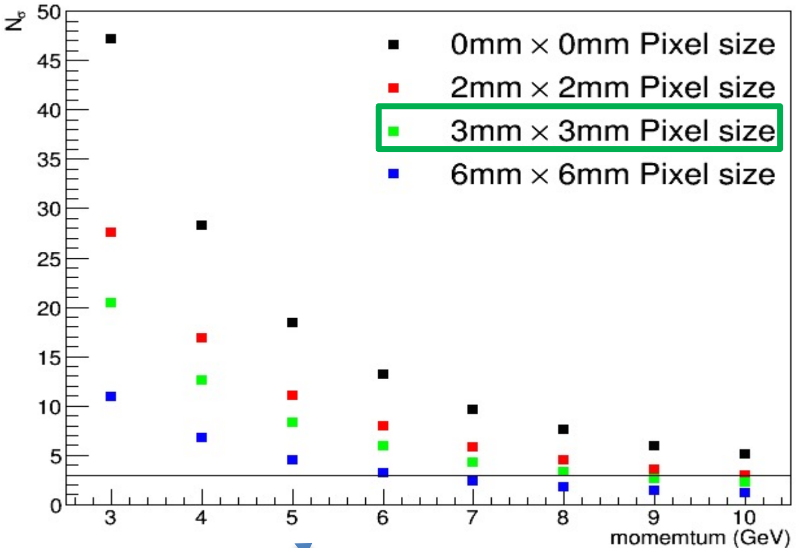
Two-Layer Proximity Focusing Design (BELLE-2 ARICH)

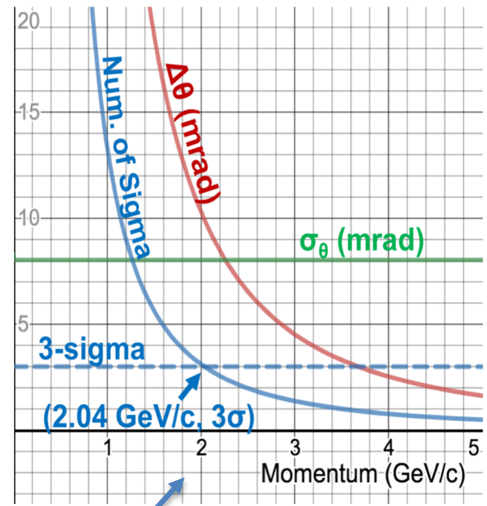




- 9 GeV/c pion beam incident at third quadrant (star) in simulation
- Ring is centered at point of incidence

Projected mRICH Performance





- Projected K/pi separation of mRICH 2nd prototype detector (**Green dots**)
- 2nd prototype detector can achieve 3-sigma K/pi separation up to 8 GeV/c

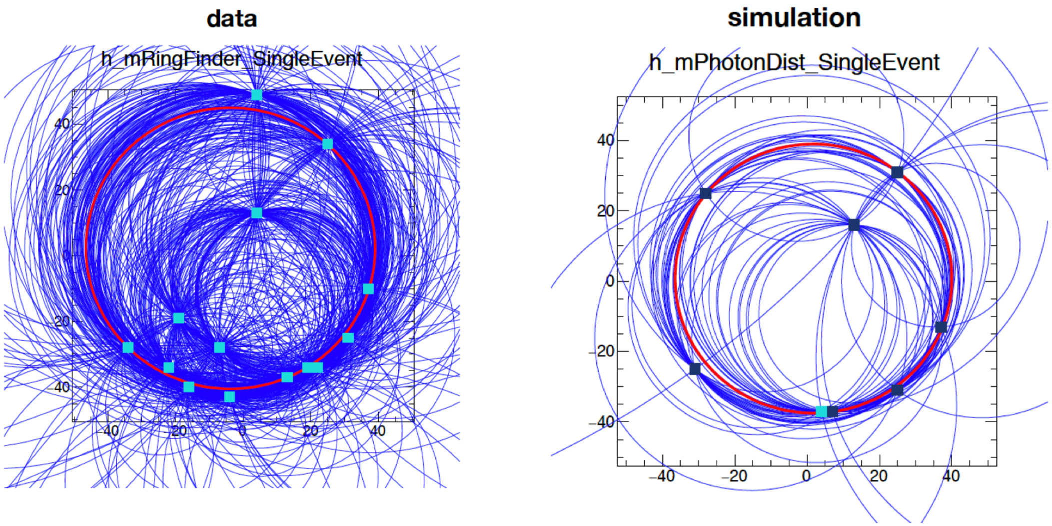
- Projected e/pi separation of mRICH 2nd prototype detector (**blue solid line**)
- 2nd prototype detector can achieve 3-sigma e/pi separation up to 2 GeV/c

Data sets taken during the second mRICH beam test at Fermilab in June/July 2018

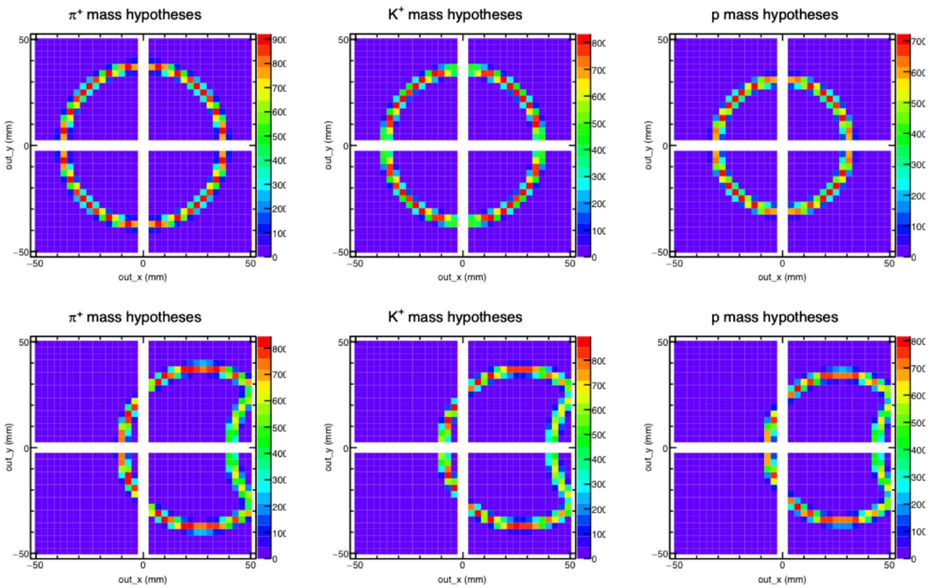
The major goal of the 2nd mRICH beam test data analysis is to **verify the PID performance at 2, 5 and 8 GeV/c**

Ring Finding Algorithm Development

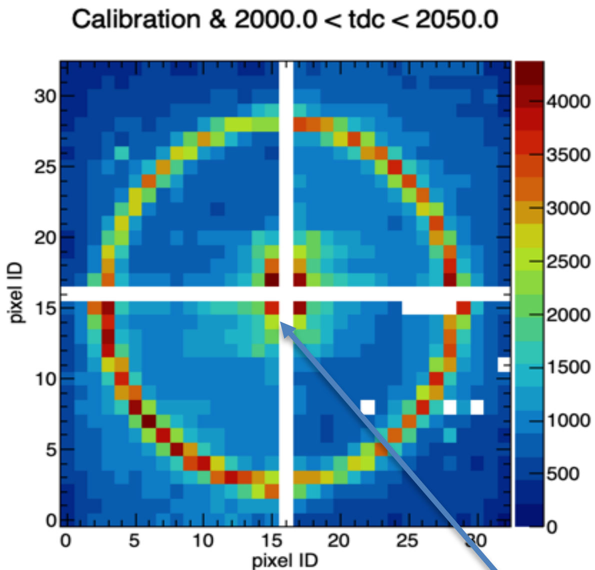
1. Perfect circle image exists only when beam hit at the center. Used Hough transformation to find the ring image and provided the baseline for consistency checks on GEANT4 simulation and analytical results.

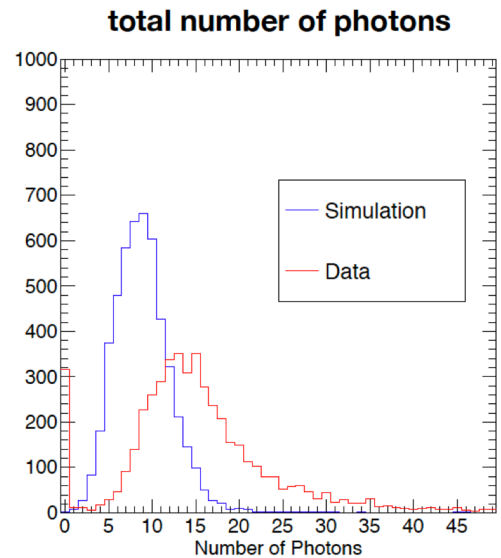


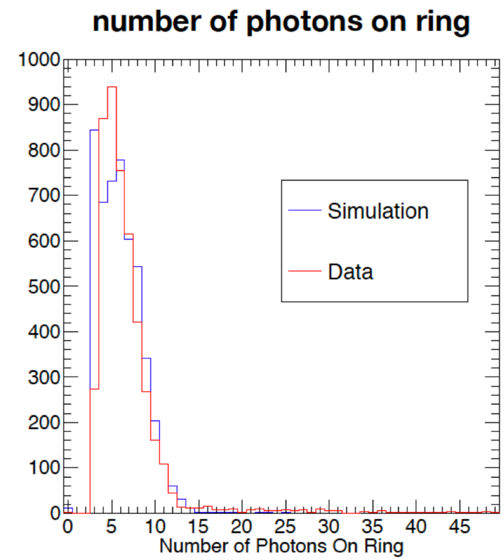
2. For other ring image forms (i.e., particles entering at off-center positions and angles), one needs to use log-likelihood method for determining ring image formation. Extensive simulation is required for generating image template database.



Confirmation of ring-centering

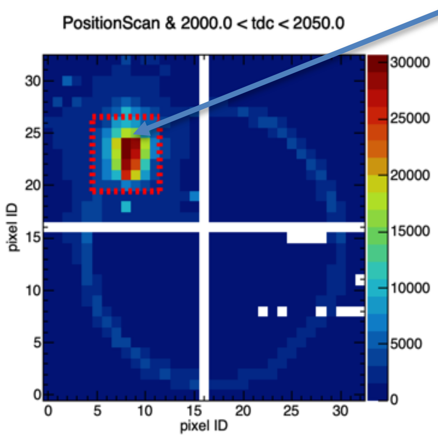




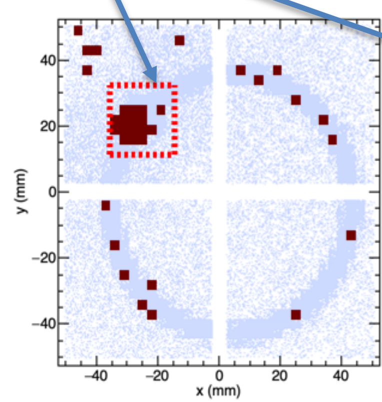


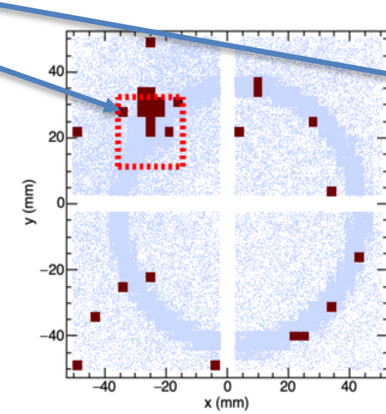
120 GeV/c proton beam spot

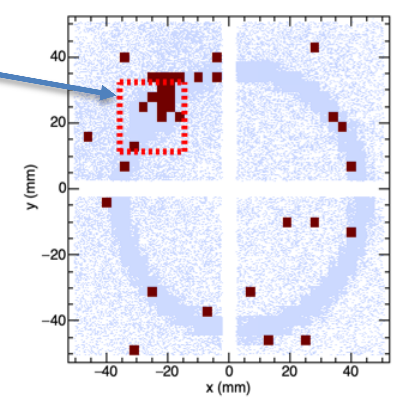
Confirmed ring centering feature of mRICH



Cumulative image



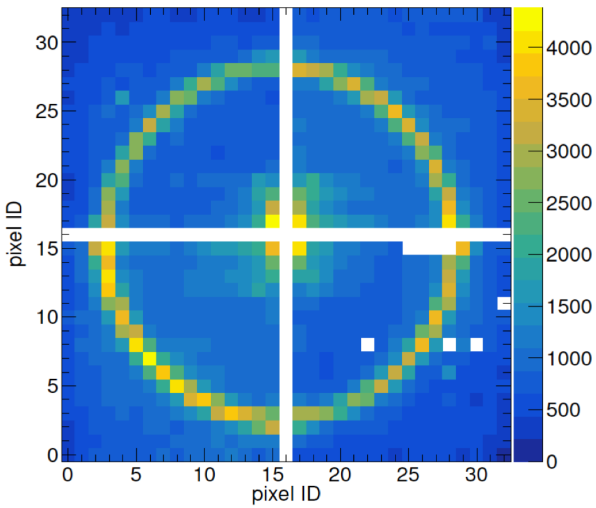


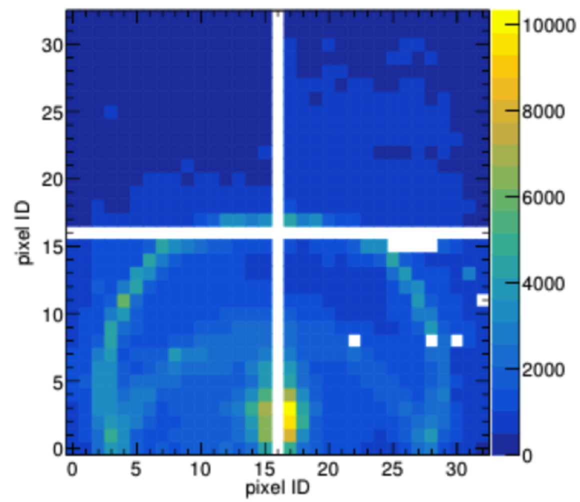


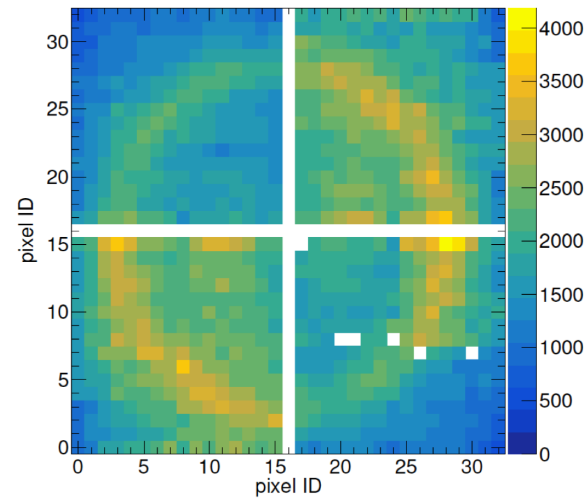
Single event samples (shaded ring images are from simulation)

Completed Data QA Analysis for the 2nd Beam Test

Examples of cumulative ring images from the second mRICH prototype beam test







Left: ring images formed by 120-GeV primary proton beam incident on the center of mRICH. White gaps are the PMT frames.

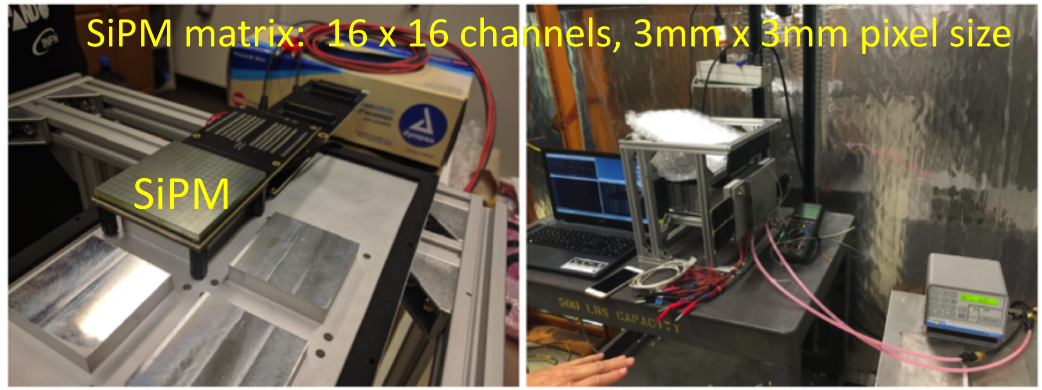
Middle: ring images from 120-GeV primary proton beam incident at an angle of 11° toward the lower section of mRICH.

Right: images from an 8-GeV meson run. The challenge of this analysis is to determine the beam position since the beam hodoscope readout was not ready for this test.

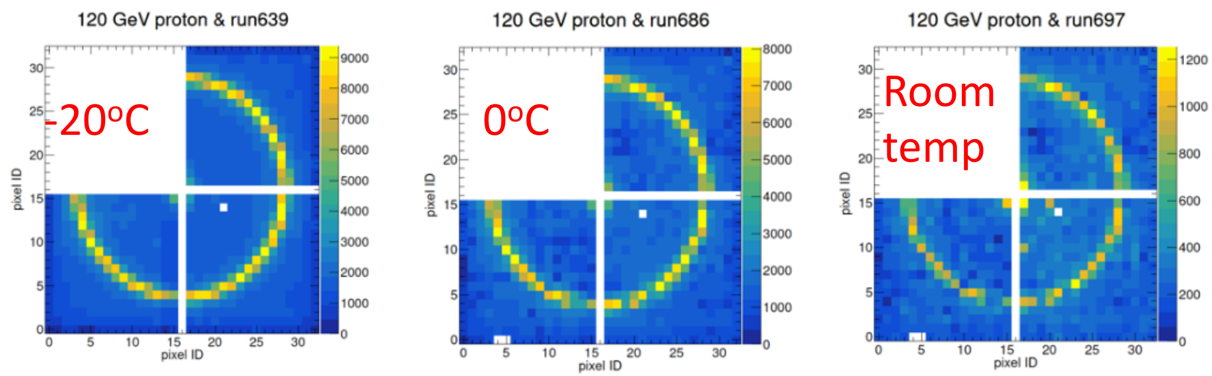
Four Hamamatsu H13700 PMTs (3mm x 3mm pixel size; 16x16 channels) were used in the test runs. In the EIC, these would be replaced by MCP-PMTs (e.g., LAPPDs) or SiPMs.

mRICH - first Ring Images from SiPM Sensors

To meet the requirement of operating photosensors in high magnetic field in EIC experiment, we successfully demonstrated ring imaging construction using mRICH in the 2nd beam test. There were only three Hamamatsu SiPM matrices available at the time of this test. Given the limited beam time, we only took data with the primary proton beam at 120 GeV with cooling temperature settings at -30°C, -20°C, -10°C, 0°C and room temperature.



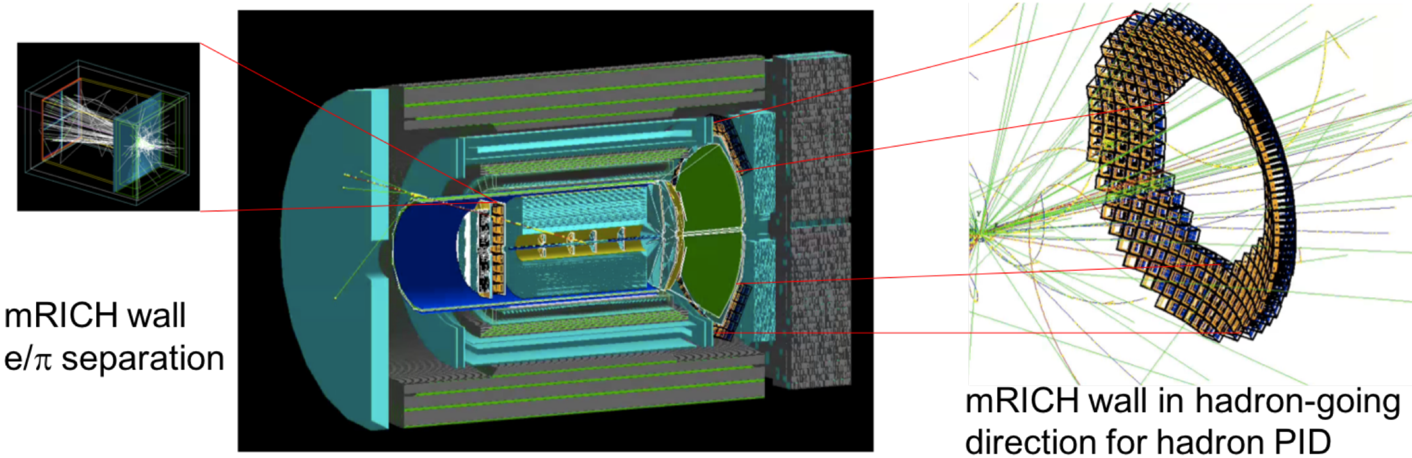
SiPM matrix assembly and Cooling setup

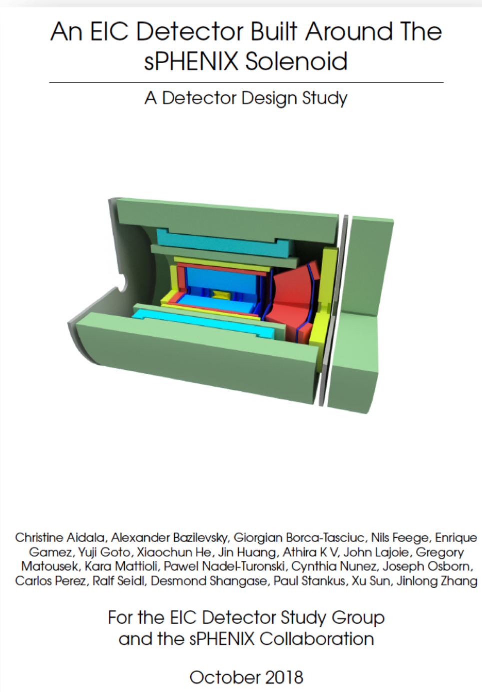


Cumulative ring images from 120 GeV/c proton beam at center

Ongoing effort: (a) photon hit timing structure; (b) noise level study; and (c) event-by-event ring image construction and fine tuning simulation.

mRICH in an EIC Detector Built Around the BaBar Solenoid





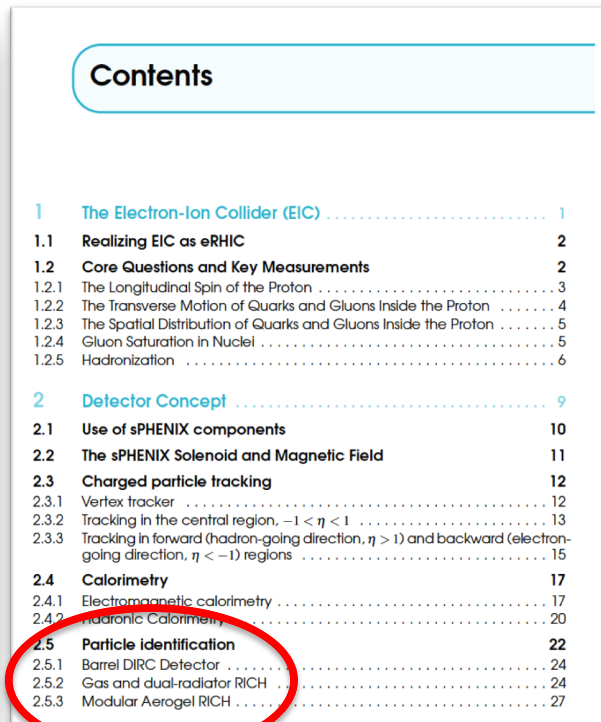
An EIC Detector Built Around The sPHENIX Solenoid

A Detector Design Study

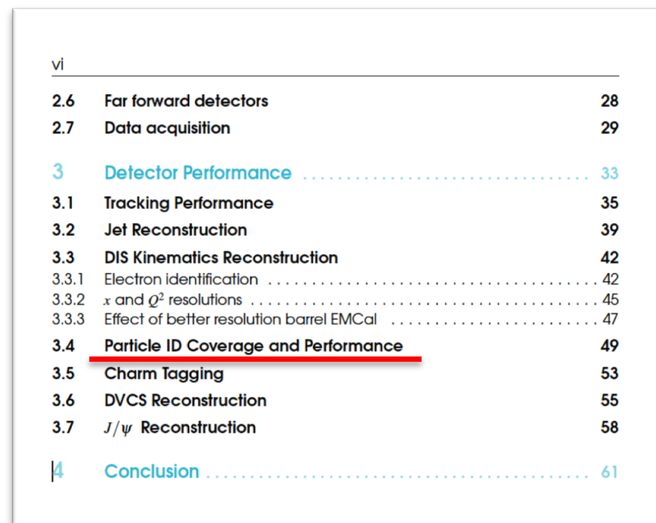
Christine Aidala, Alexander Bazilevsky, Giorgian Borca-Tasciuc, Nils Feege, Enrique Gamez, Yuji Goto, Xiaochun He, Jin Huang, Athira K V, John Lajoie, Gregory Matousek, Kara Mattioli, Pawel Nadel-Turonski, Cynthia Nunez, Joseph Osborn, Carlos Perez, Ralf Seidl, Desmond Shangase, Paul Stankus, Xu Sun, Jinlong Zhang

For the EIC Detector Study Group and the sPHENIX Collaboration

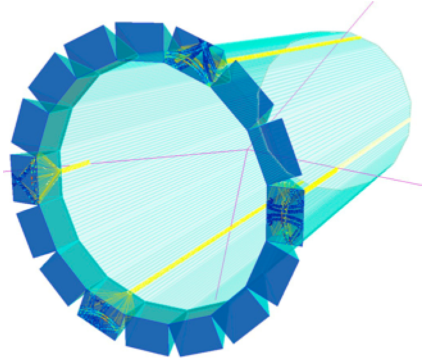
October 2018



Contents



High-performance DIRC (hpDIRC)



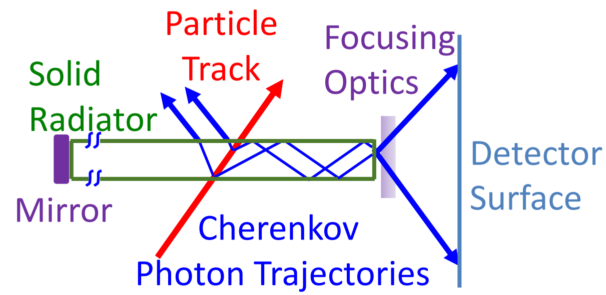
Goal:

- Very compact device with coverage beyond 10 GeV/c for p/K, 6 GeV/c for π/K, and 1.8 GeV/c for e/π, pushing performance well beyond state-of-the-art
- First DIRC aiming to utilize high-resolution 3D (x,y,t) reconstruction

FY 20 Activities:

- Transfer the PANDA DIRC Prototype to the U.S.
- Develop Geant simulation for hpDIRC prototype in beam test environment
- Upgrade laser setup for characterization of the optical properties of the three new lens prototypes
- Finalize radiation hardness study of candidate lens materials using both neutron and gamma sources
- Study feasibility of "mini-DIRC" for near-beam ion identification

hpDIRC – overview



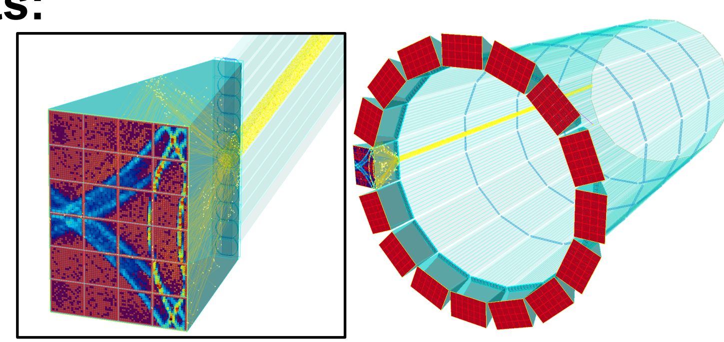
High performance DIRC in Geant 4

hpDIRC simulations

- Parametrization of the hpDIRC baseline design performance to be used as input to the fast EIC detector simulations

Development of 3-layer lens and experimental tests:

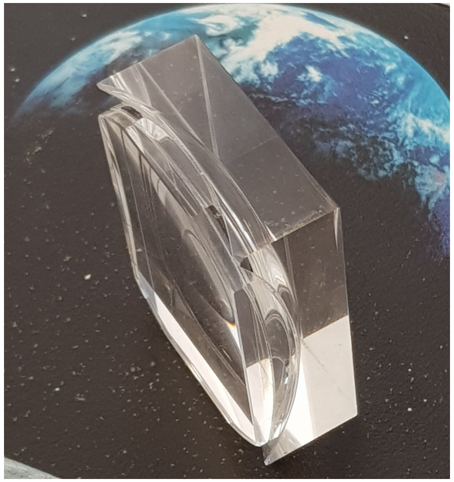
- Detailed radiation hardness test in ^{60}Co source confirmed sapphire and PbF_2 to be radiation hard
- Planned upgrade of the laser setup to characterize three new lens prototypes



The hpDIRC prototype:

- Last PANDA Barrel DIRC test beam prototype identified the potential for a significant reduction in the number of sensors required to cover the detector plane
- PANDA DIRC prototype transfer to U.S. a key step towards hpDIRC prototype

Square spherical 3-layer lens prototype

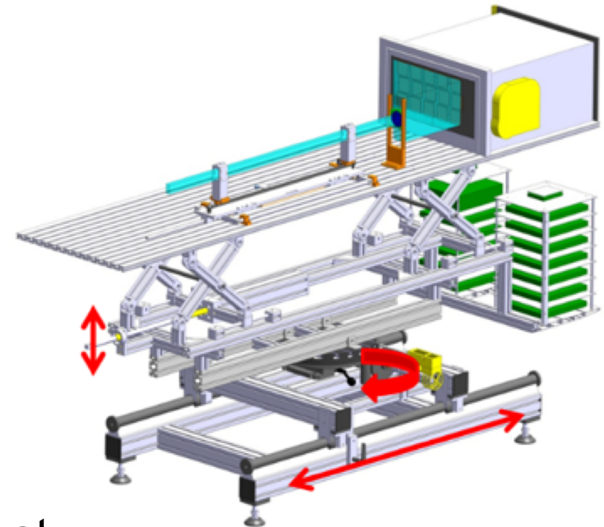


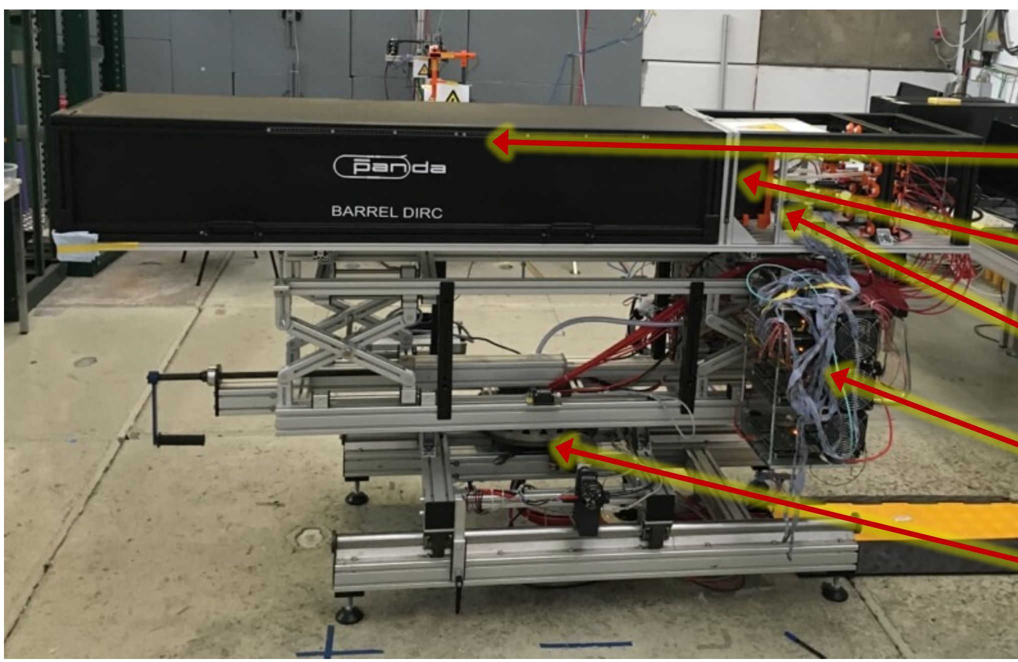
„mini-DIRC" for near-beam ion identification

- Proposed pilot study to evaluate the feasibility of „mini-DIRC" for the forward near-beam to detect scattered light ions and heavy-ion fragments.

hpDIRC – transfer of PANDA prototype to U.S.

- PANDA Barrel DIRC prototype entering retirement after conclusion of their R&D phase
- Available components include:
  fused silica bar and plate, fused silica prism, lenses,
  few Planacon MCP-PMTs (6.5mm pixels, 25μm pores)
  with PANDA DAQ cards (PADIWA/TRB, $\sigma_t \approx 200$ps),
  mechanical support (incl. rotation stage), dark box.
- FY20: transport to U.S. (most likely Stony Brook), set up DAQ system, test with laser pulser to prepare for beam teat.





Dark box for optics (bar, lens, prism)

MCP-PMT array

Frontend electronics (PADIWA) (air-cooled)

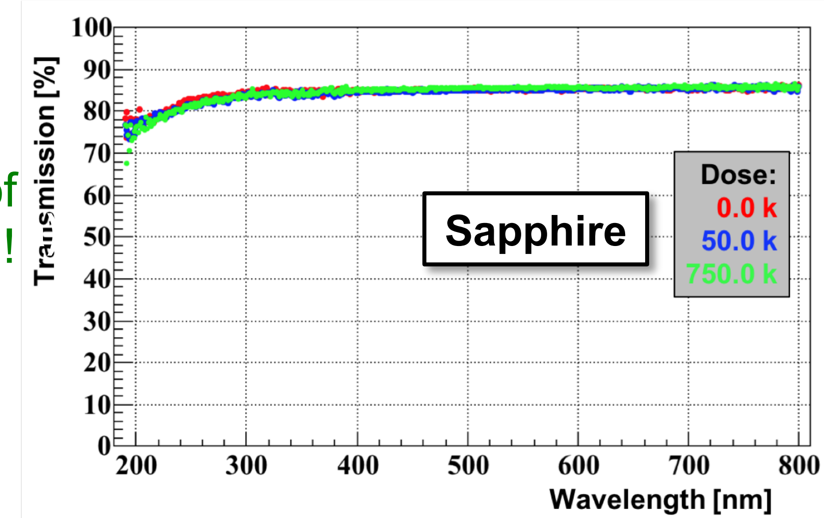
DAQ boards (TRB)

Rotation stage (remote controlled)

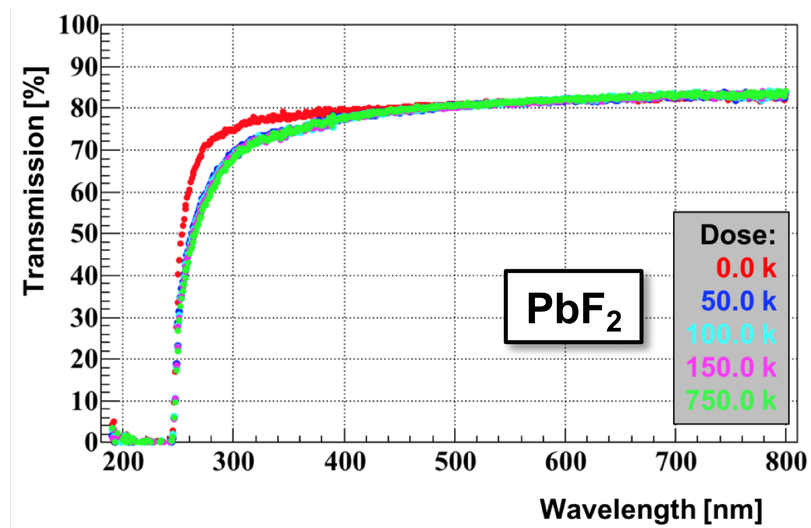
hpDIRC – radiation hardness of 3-layer lens

^{60}Co irradiation results

- Five materials studied; radiation hardness of sapphire and PbF_2 confirmed up to 750krad!
- Sapphire and PbF_2 prototype lenses purchased
- Further studies including and other candidates tests in progress
- Radiation hardness to neutrons planned for FY20



Tested samples



hpDIRC – production and validation of rad hard lenses

Two radiation-hard 3-layer spherical prototype lenses currently in production, will be available early fall 2019.

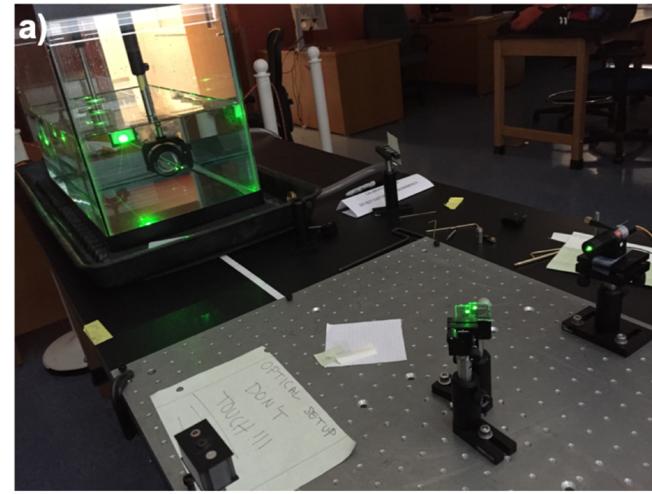
Mapping focal plane of cylindrical 3-layer lens:

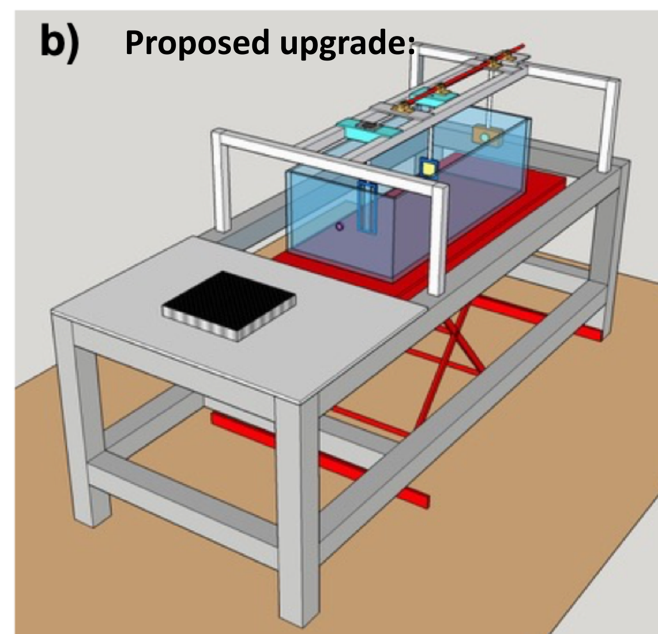
- Results of measurements confirm desired flat focal plane for centered laser beams on the lens

Upgrade of setup will simplify the calibration and the exchange of lenses, and increase the precision and speed of the measurements

- More precise measurements including off-center laser beams planed for next year.
- Combined results for six lens prototypes planned to be published in FY20.

Laser setup at ODU to map the focal plane
Current setup:



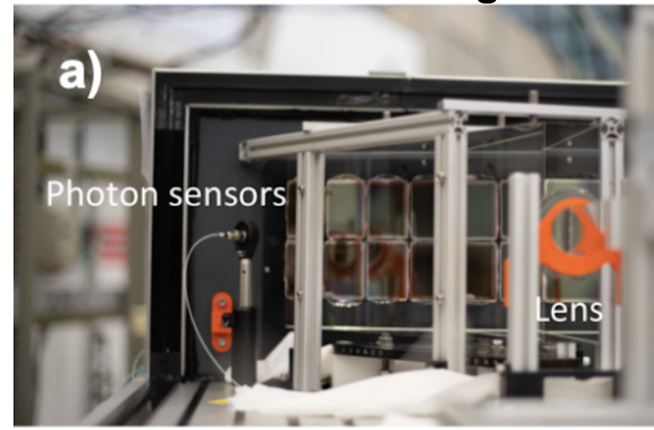


hpDIRC – validation in CERN test beams

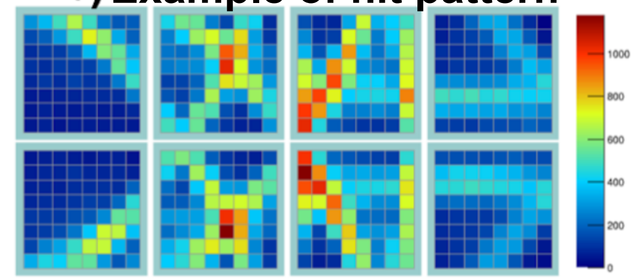
PANDA Barrel DIRC prototype at CERN PS in July/Aug 2018: reduced number of MCP-PMTs.

- Caveat: larger sensor pixels, slower electronics than EIC DIRC → PANDA goal: 3σ π/K separation @ 3.5 GeV/c
- Optics similar to EIC DIRC design:
  narrow bar, fused silica prism, 3-layer spherical lens
- Reduced MCP-PMT coverage by 33% compared to 2017, gaps near prism sides (data analysis ongoing)
- Measured key quantities: photon yield, Cherenkov angle resolution per photon and per particle, and π/K separation power – all in good agreement with simulation (used for EIC DIRC)
- PID performance in 2018 close to 2017 results (photon yield lower but π/K separation still > 3σ)
- Impact of reducing number of sensors promising, has to be tested in EIC simulation

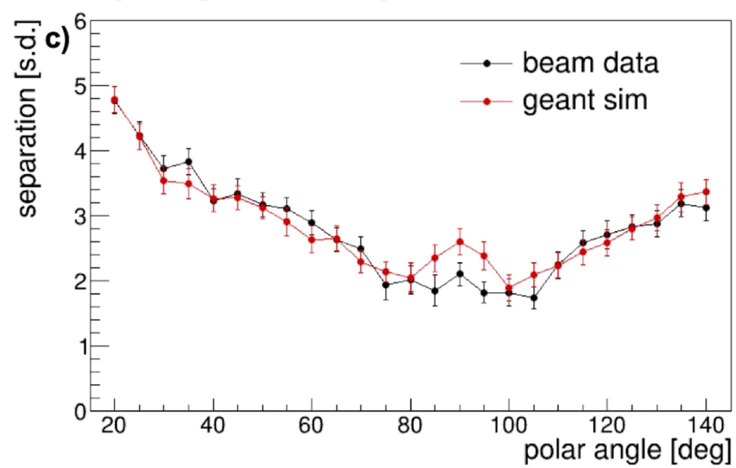
2x4 MCP-PMT arrangement



b) Example of hit pattern



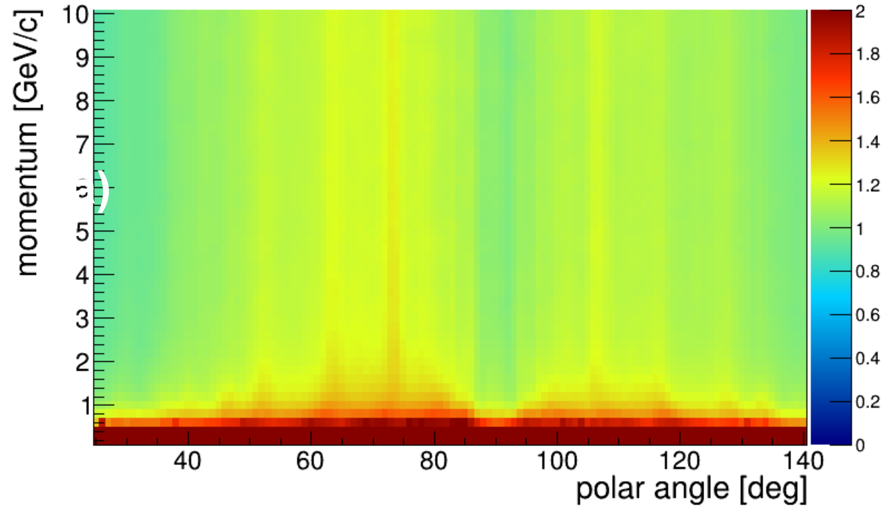
π/p separation power at 7 GeV/c



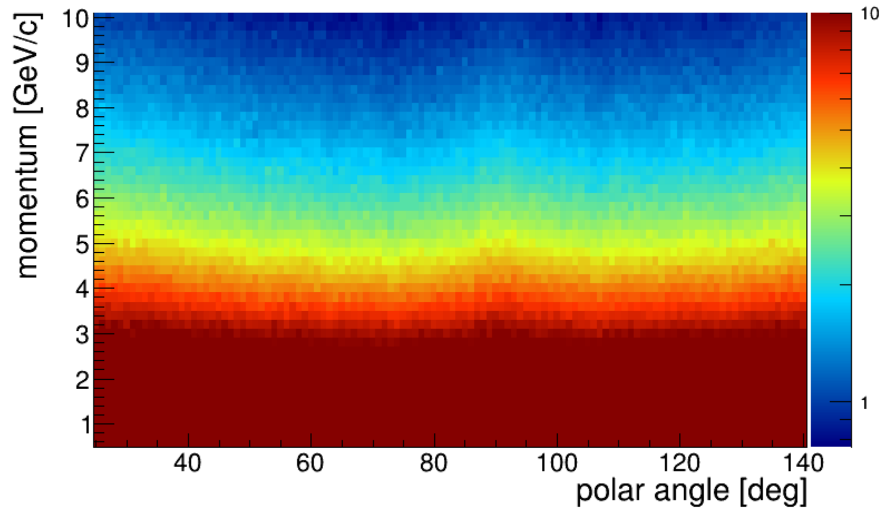
hpDIRC – parametrization of hpDIRC for fast simulation

- A special C++ class was designed and released to the EIC software community
- Geant4 simulation of the current hpDIRC baseline design used to calculate the Cherenkov track resolution (CTR)
- The fast simulation returns the deviation of the smeared Cherenkov angle from the expected values in units of CTR
- The derived π/K separation power in standard deviations is a result of the fast reconstruction

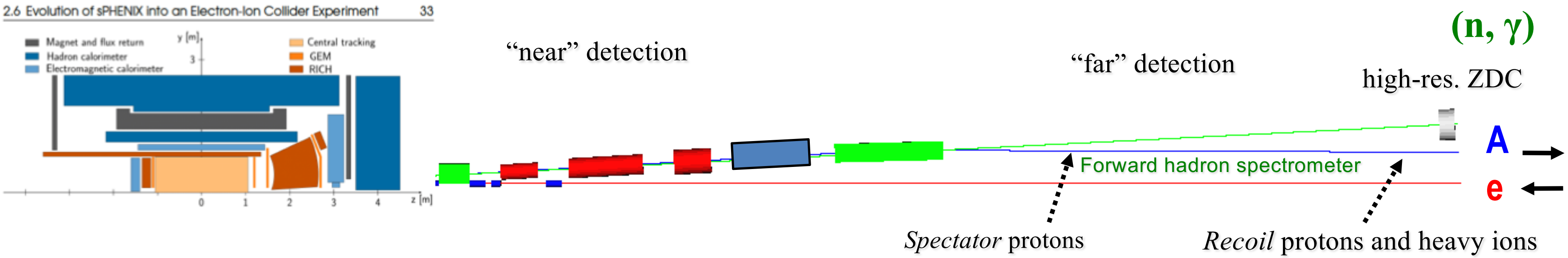
Geant4 simulated Cherenkov track resolution



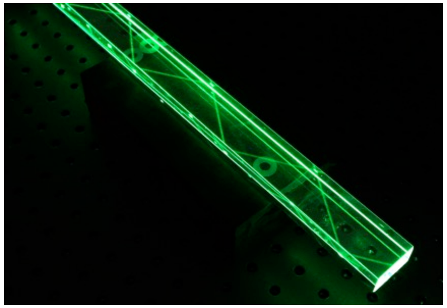
Example of derived π/K separation power (tracking resolution of 0.5 mrad)



PID for ions at very forward angles



- Detection of nuclei with rigidities (A/Z) close to that the beam require a dedicated “far” spectrometer where the beam is small and dispersion large.
- To identify the ion we need both A/Z and an independent measurement of Z. The requirement for sensitivity in Z^2 about 2%.
- A ”mini-DIRC” can produce close to 100,000 photons (<< 1% error) in a few mm of fused silica – but which expansion volume geometry and photosensor combination will be best at counting them precisely?
- A pilot study is proposed as a new R&D project this year by the EIC PID consortium,



A “mini-DIRC” inside a Roman pot at the downstream focus can identify ions to ~1% in Z^2

Photosensors and Electronics

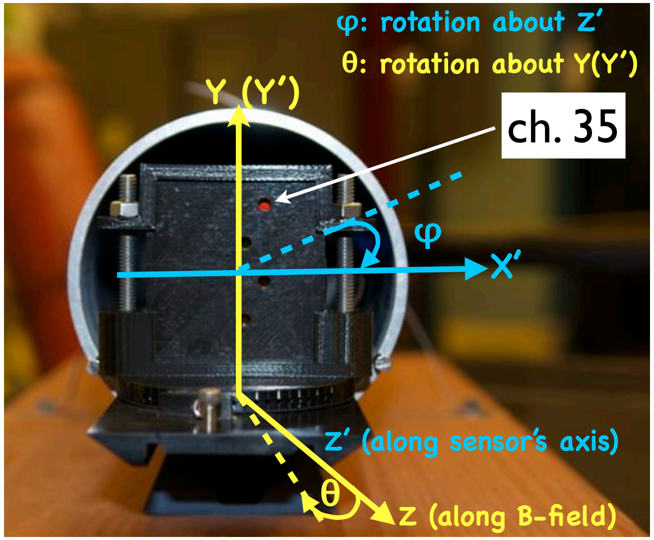
Goals:

- To evaluate commercial photosensors for EIC PID detectors and to develop alternative, cost-effective photosensors (LAPPDs).
- To develop readout electronics for PID detector prototypes.

FY20 Activities:

- Evaluation of photosensors in high-B fields at JLab.
- Adaptation of LAPPDs to EIC requirements at ANL.
- Development of readout electronics (U. Hawaii and INFN-Ferrara) for Cherenkov Detectors prototype tests.

Sensors in High-B Fiels



Goals:

- To evaluate commercial photosensors for EIC PID detectors in order to identify the limitations of current PMTs design and operational parameters for High-B operations

FY20 Activities:

- Detailed studies of gain, ion feedback, and timing-resolution of latest-generation 10-mum Planacon as a function of B, HV, and sensor orientation relative to field direction.

Sensors in High-B Fields

FY19 - funded activities

- Planacon B-field studies of ion feedback: analysis of data completed
- Studies of Planacon gain evaluation with various amplifiers and amplifications: data taking completed; analysis in progress
- Studies of Planacon efficiency evaluation with different readouts: data taking completed; analysis in progress

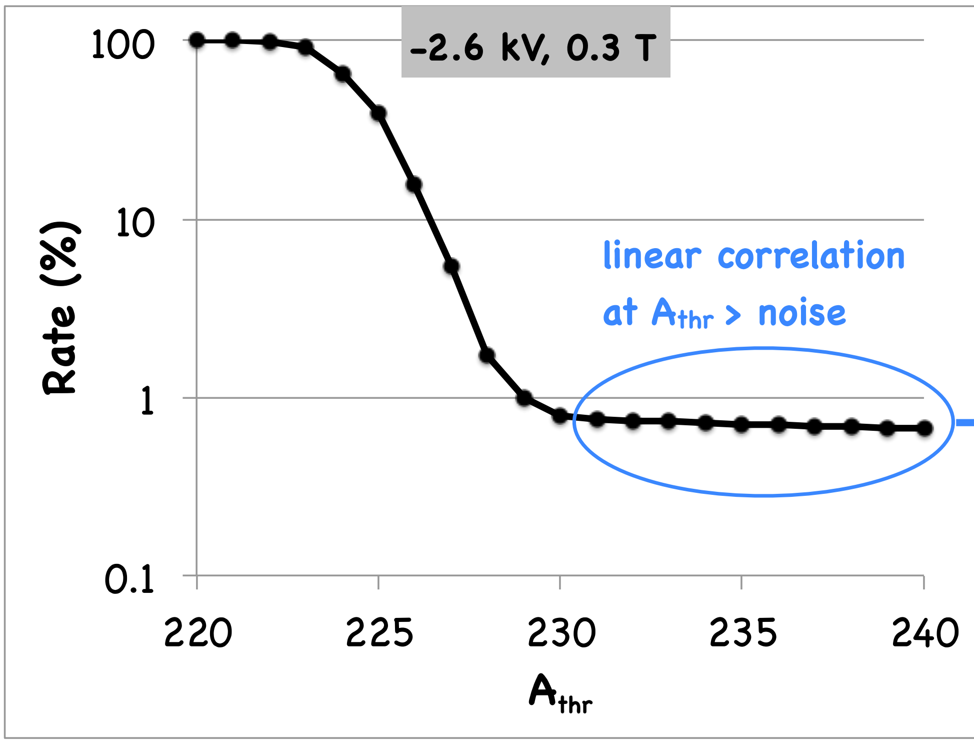
FY20 - proposed activities

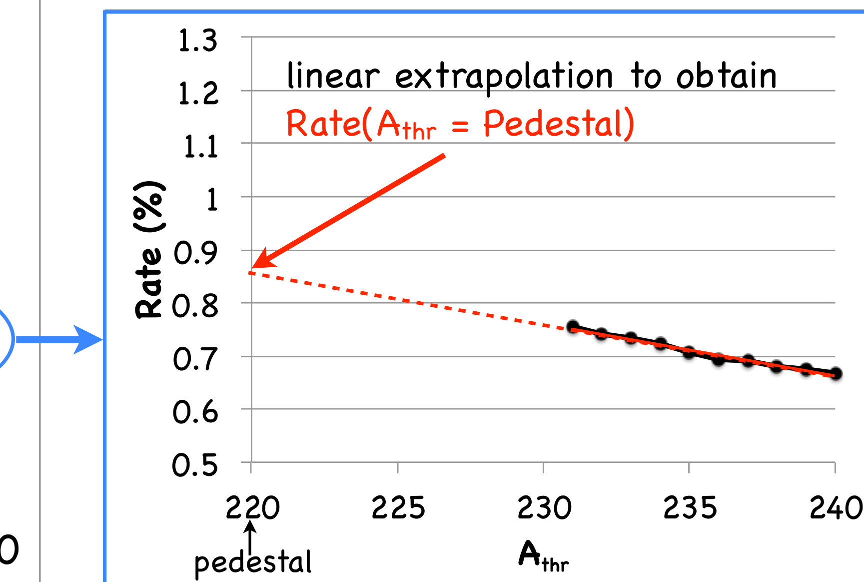
- Evaluation of gain, ion feedback, and timing-resolution of latest-generation 10-mum Planacon, XP85122-S, as a function of B, HV, and sensor orientation relative to field direction.
- Comprehensive gain and timing studies of XP85122-S with changing $HV_{Cth\text{-}MCP1}$, $HV_{MCP1\text{-}MCP2}$, $HV_{MCP2\text{-}Anode}$.

Results from FY19 Ion-Feedback Studies

10-µm Planacon: Ion Feedback

- Too low A_{thr} leads to an overestimate of the ion-feedback rate due to some noisy waveforms. $A_{thr}=233$ is the best empirically found value for Summer 2018 data.
- **Problem:** Waveforms where $A_{signal} < A_{thr}$ or/and $A_{ions} < A_{thr}$ are not taken into account.

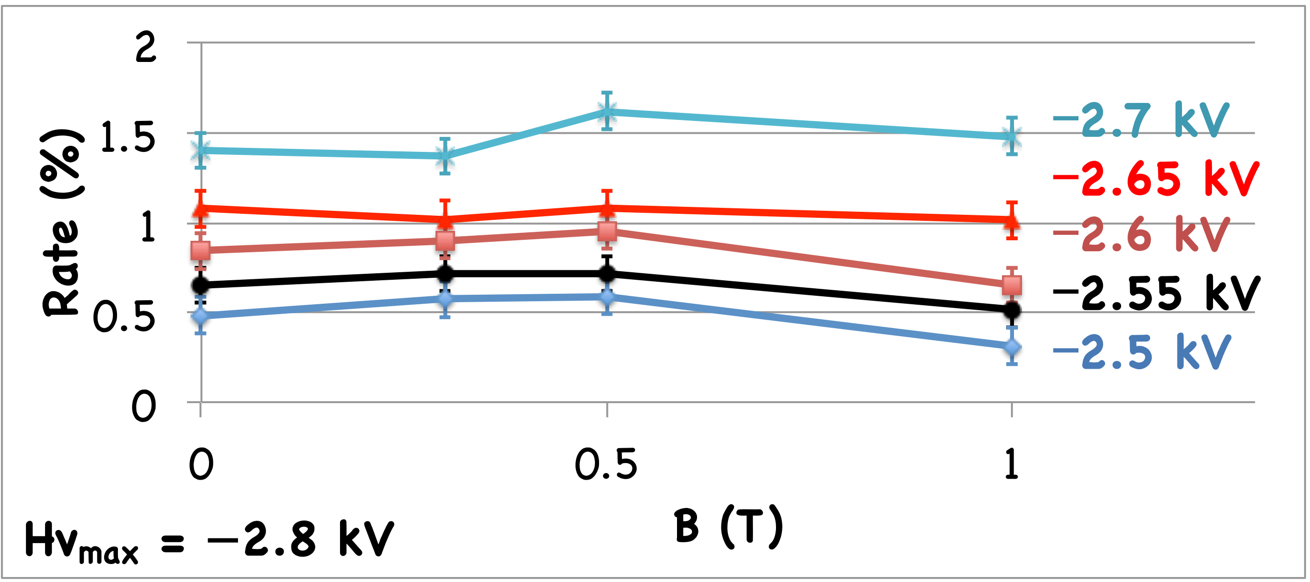


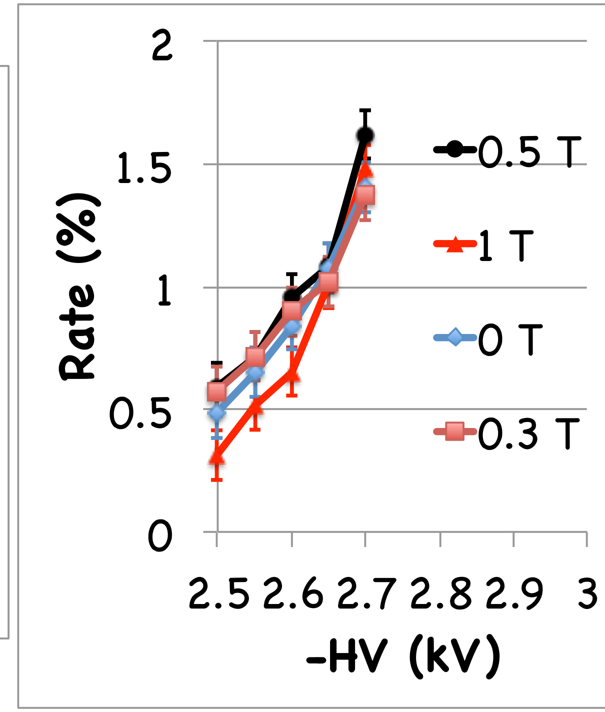


- *Rate* is evaluated over a range of A_{thr}. *Rate*(A_{thr}=Pedestal) is obtained from a linear fit to the high-A_{thr} tail. This is the best estimate of the true ion rate, i.e. as would be obtained if there were no noise on the waveform, but only signal(s).

Results from FY19 Ion-Feedback Studies

10-µm Planacon: Ion Feedback





$\Delta = Rate(\mathrm{A_{thr}}=\mathrm{Pedestal}) - Rate(\mathrm{A_{thr}}=233)$. $\overline{\Delta} = 0.13$. Reported above: $Rate(\mathrm{A}_{thr}=233) + \overline{\Delta}$

- At all voltages the ion rate is below 2%.
- Results suggest that ion-feedback is primarily driven by HV.
- Ion-feedback rate dependence on B-field magnitude is relatively weak.
- Method established; ion rate can be monitored in experiments using calibration data.

MCP-PMT / LAPPD^{TM}

Goal:

Adapt LAPPD^{TM} to the EIC requirements:
Highly pixelated LAPPD^{TM} working at 2~3 Tesla, to be used as photosensors for mRICH, dRICH, and DIRC detectors, as well as TOF applications.

FY 19 Progress:

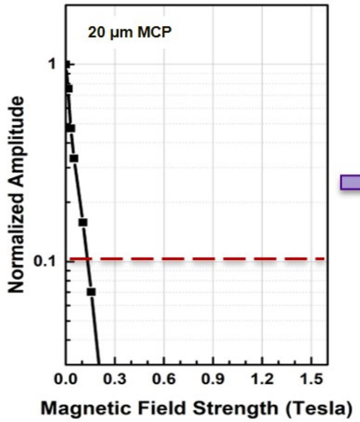
- Magnetic field tolerance up to 1.5 T achieved, fast timing improvement
- Pixel MCP-PMT readout with glass/fused silica anode plate
- MCP-PMT simulation

FY 20 Activities

- Integrate magnetic field tolerant design with glass pixelated readout
- Advantage/disadvantage comparison of glass pixel vs. ceramic pixel
- MCP-PMT simulation with magnetic field
- Effort enhancement with electronics, DIRC, dRICH and mRICH sub-systems

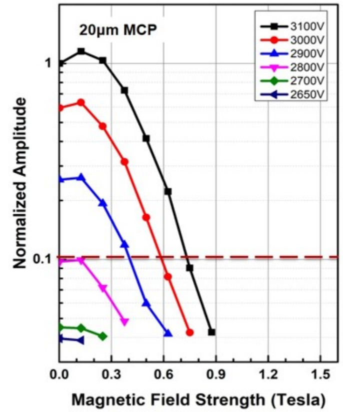
Improvement of Argonne MCP-PMT Performance in Magnetic field

ANL version 1
Internal resistor chain



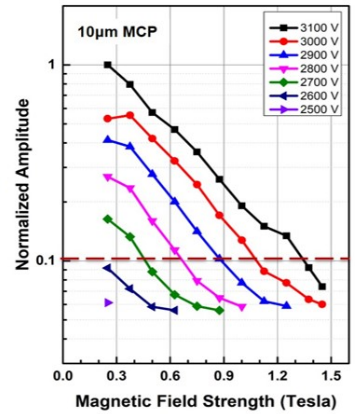
0 < B < 0.15 T

ANL version 2
IBD design 20 µm MCP



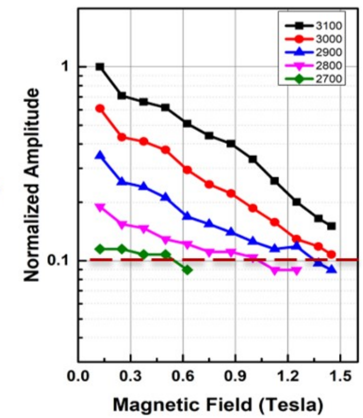
0 < B < 0.7 T

ANL version 3
IBD design 10 µm MCP



0 < B < 1.3 T

ANL version 4
IBD design 10 µm MCP
reduced spacing



0 < B < at least 1.5 T

CLEO-II or BaBar Magnet: 1.5T

- Optimization of biased voltages for both MCPs: **version 1 -> 2**
- Smaller pore size MCPs: **version 2 -> 3**
- Reduced spacing: **version 3 -> 4**
- Further improvement if needed:
  Smaller pore size is planned: 6 µm, version 4 -> 5 (future)

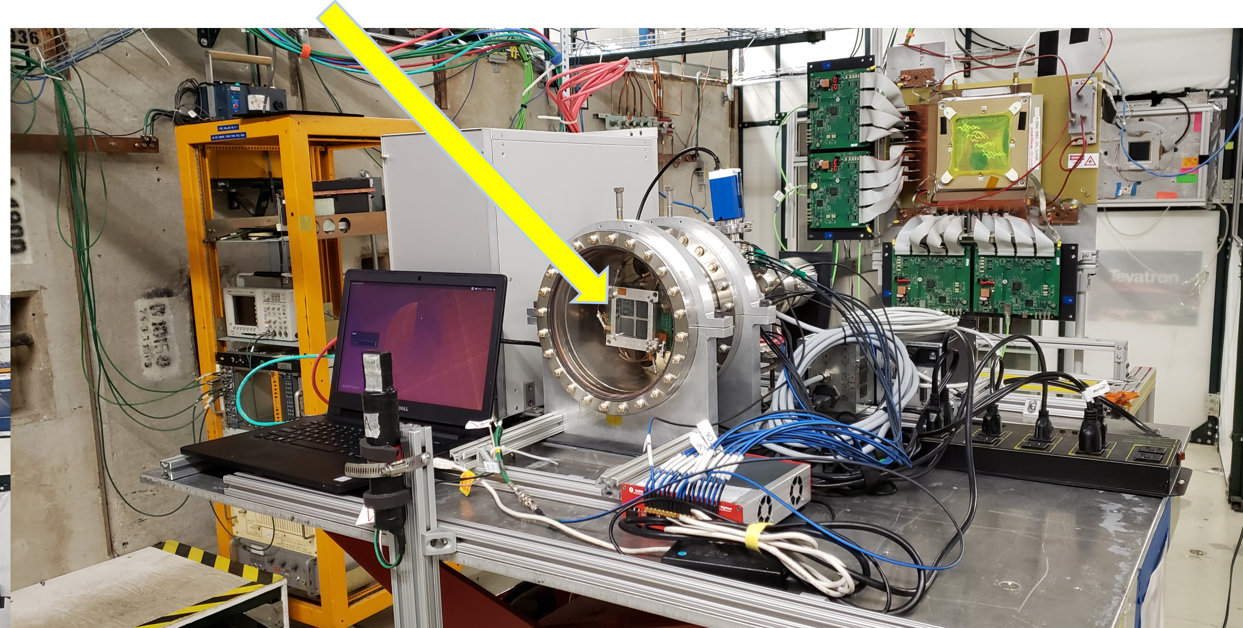
Argonne MCP-PMT Performance comparison – timing and B-field

		ANL Version 2 Standard 20 μm MCP-PMT	ANL Version 3 10 μm MCP-PMT without reduced spacing	ANL Version 4 10 μm MCP-PMT with reduced spacing
MCP	Pore size	20 μm	10 μm	10 μm
	Length to diameter ratio (L/d)	60:1	60:1	60:1
	Thickness	1.2 mm	0.6 mm	0.6 mm
	Open area ratio	60 %	70 %	70 %
	Bias angle	8°	13°	13°
Detector geometry	Window thickness	2.75 mm	2.75 mm	2.75 mm
	Spacing 1	3.25 mm	2.25 mm	2.25 mm
	Spacing 2	1.75 mm	2.0 mm	0.7 mm
	Spacing 3	2.0 mm	4.0 mm	1.1 mm
	Shims	0.3 mm	0.3 mm	0.3 mm
	Tile base thickness	2.75 mm	2.75 mm	2.75 mm
MCP-PMT stack	Internal stack height	**9.70 mm**	**9.75 mm**	**5.55 mm**
	Total stack height	15.20 mm	15.25 mm	11.05 mm

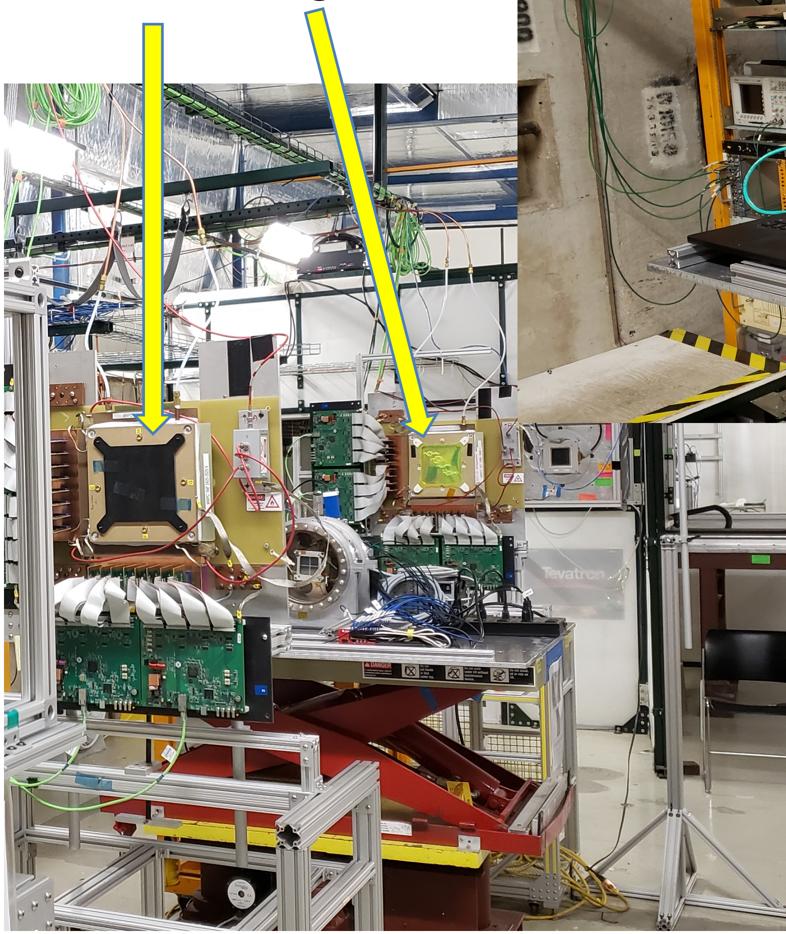
Gain Characteristic	Gain	1.35×10^7	3.05×10^6	2.0×10^7
Time Characteristic	Rise time	**536 ps**	**439 ps**	**390 ps**
	Timing distribution RMS	204 ps	106 ps	190 ps
	System resolution	70.0 ps	37.2 ps	43 ps
	Time resolution	**63 ps**	**20 ps**	**30 ps**
	Differential time spread	11 ps	7 ps	5 ps
	Spatial resolution	0.83 mm	0.53 mm	0.38 mm
Magnetic Field	Magnetic field tolerance	**0.7 Tesla**	**1.3 Tesla**	**Over 1.5 T**

Fine pixelated readout through glass/fused silica anode

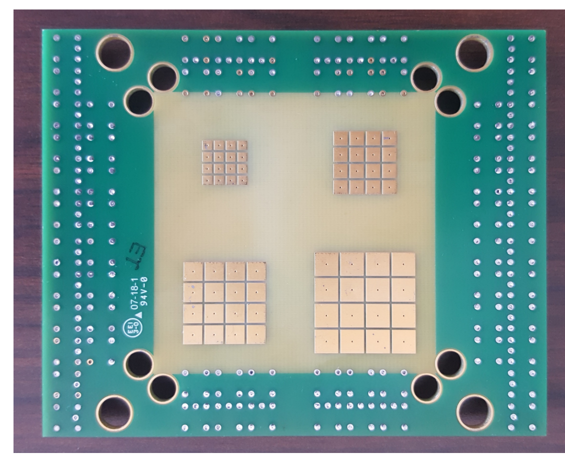
Argonne MCP stack (glass anode) in Fermilab test beam



MWPC tracking used

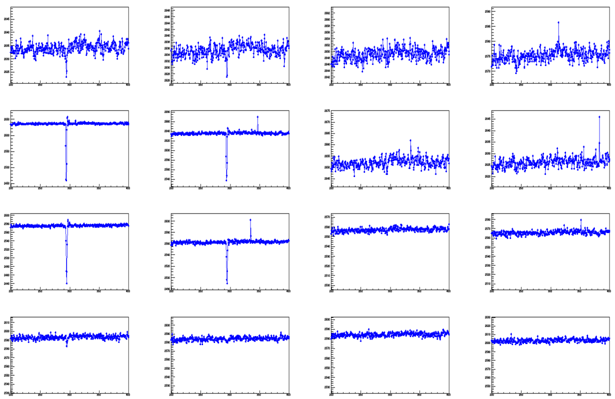


4 different pixel sizes (2x2,3x3,4x4and 5x5mm^2) implemented for testing

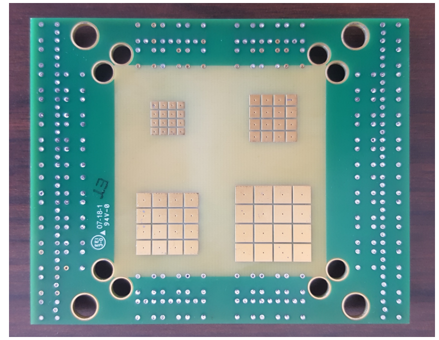


Event Display

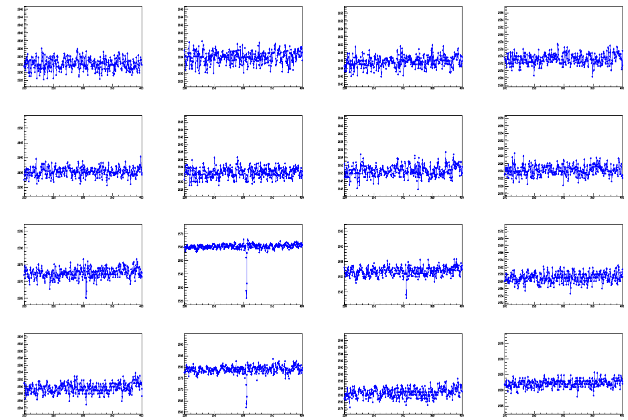
2x2 mm^2 pixels



2x2 mm^2 pixel size is too small, signals are spread onto several pixels.



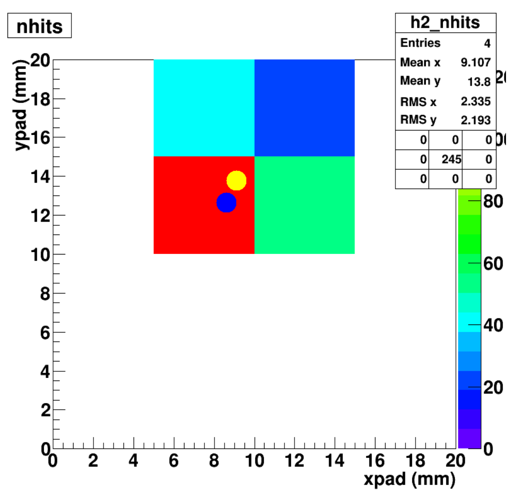
4x4 mm^2 pixels

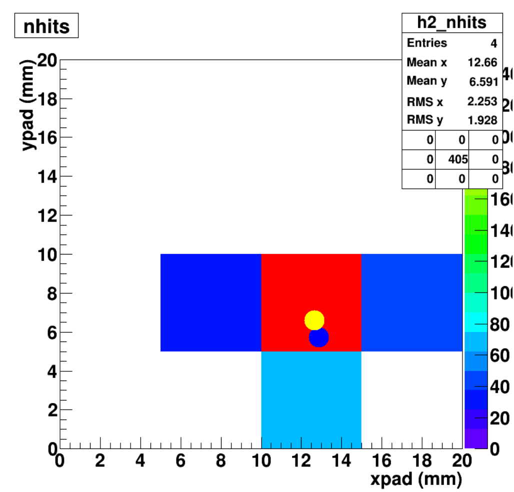


Larger pixel size, signals are more confined, mainly on one pixel.

Center of mass calculation for hit position

5x5 mm^2 as example



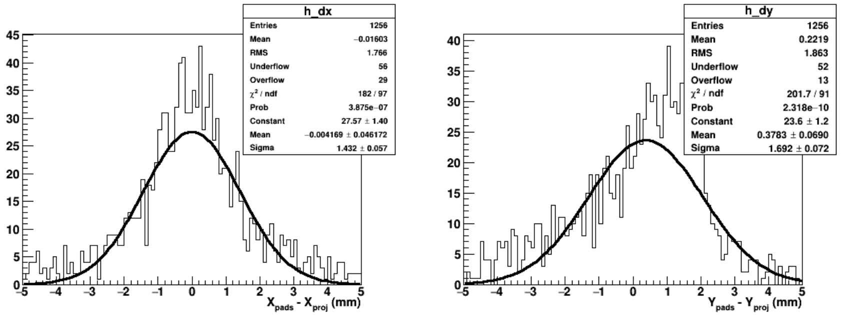


Yellow dot is the center of mass of pad hits; Blue dot is projection from MWPC tracking

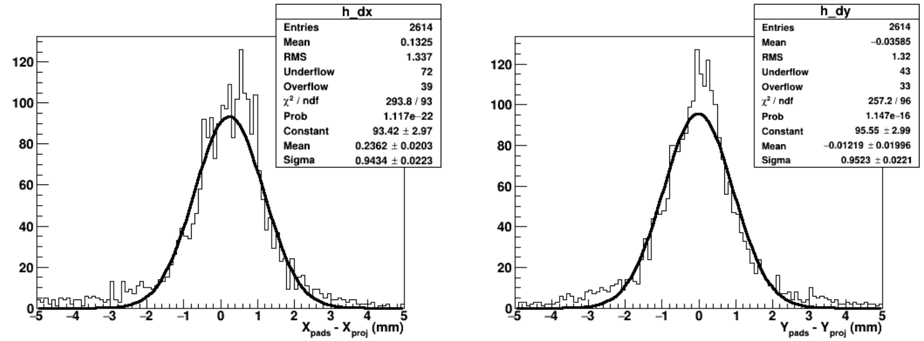
Position resolution

Difference between the pad mean position (CG) and the track pointing

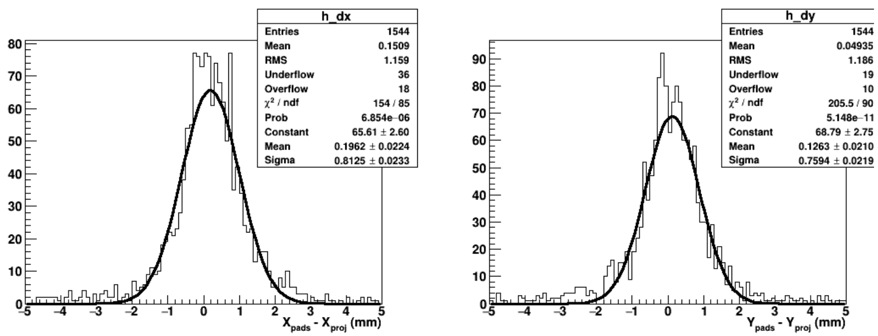
2x2 mm



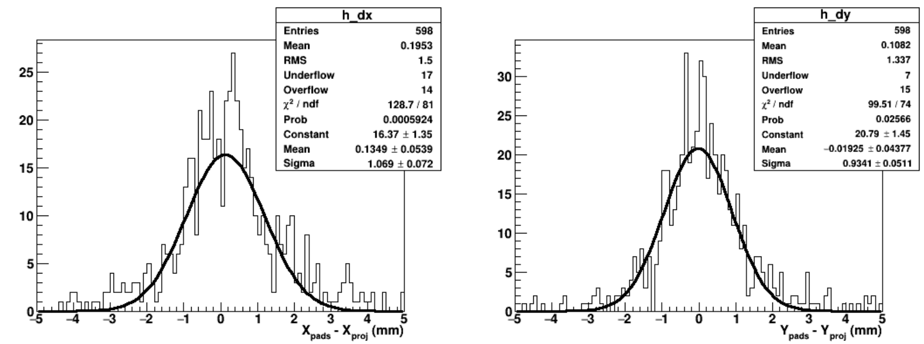
3x3 mm



4x4 mm



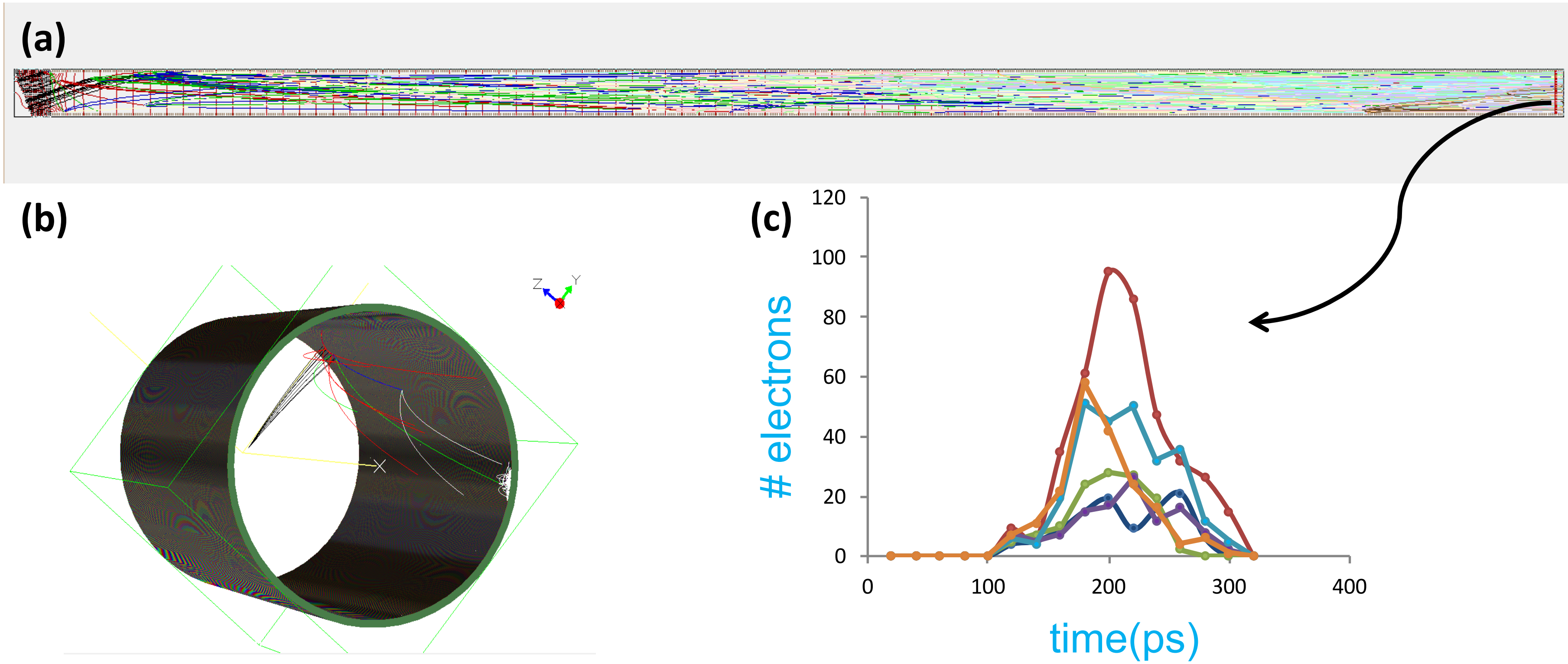
5x5 mm



	X res (mm)	Y res (mm)
2x2 mm	1.4	1.7
3x3 mm	0.94	0.95
4x4 mm	0.81	0.76
5x5 mm	1.1	0.97

- All resolutions ~1 mm, satisfy the requirement for the EIC.
- Potentially limited by track pointing resolution capability of MWPCs (1 mm pitch)
- 2x2 may be worse due to leakage of signals (poor containment since it is a smaller area)

MCP-PMT simulation



Single MCP simulation with SIMION software, effort launched at ANL:

(a) Side view of the secondary electron emission process in a single pore with multiple electrons

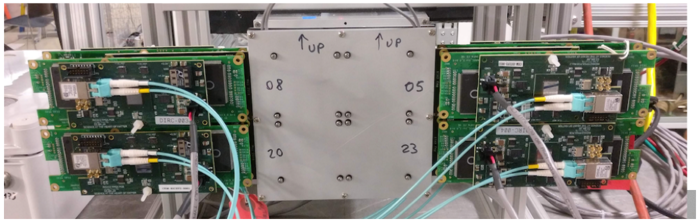
(b) 3-D view of the secondary electron emission process in a single pore at the beginning of the pore;

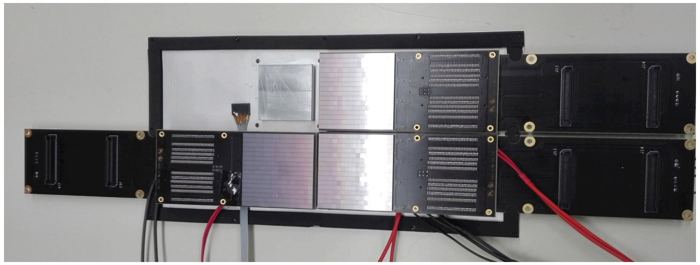
(c) Dependence of a series of simulated detection pulses on the time relative to the initial electron time: times are consistent pulse to pulse.

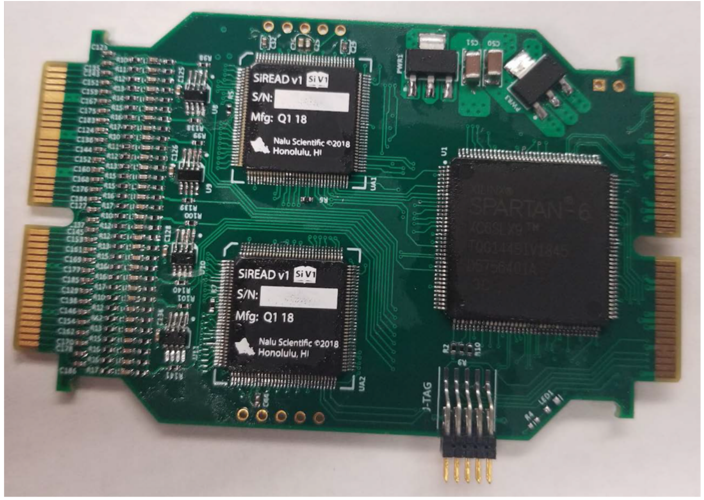
MCP-PMT / LAPPD – Conclusion

- MCP-PMT / LAPPD achieved magnetic field tolerance of over 1.5 Tesla and time resolution RMS of ~100 ps
- MCP-PMT readout with 3x3 mm^2 pixel size and position resolution of <1 mm was demonstrated.
- MCP-PMT simulation with SIMION software effort was launched.

Readout Electronics







Goal:

- Develop an integrated suite of readout electronics for the different photosensors used for all the Cherenkov detectors and prototypes.
- Provide a reference readout system for prototypes performance assessment
- Developed a generic DAQ system compatible with the Consortium needs
- Test applications with innovative sensors (SiPM)

FY 20 Activities:

- Moving from the TARGETX (Belle-II) to the new SiREAD chip
- Development of pulsed laser test benches for detailed characterization
- Radiation tolerance study for SiPM

Nalu Scientific
Data Acquisition Systems

Electronics – overview

Requirements

- Need to read out several photosensors (MaPMTs, MCP-PMTs, and SiPMs) with similar sensor and pixel size (16x16 array of 3 mm pixels)
  - DIRC also requires good timing (<100 ps)
- Goal is to have common front end electronics with good timing that can be used for all sensors and detectors (mRICH, dRICH, DIRC)

Implementation

- The Maroc-based CLAS12 front end has been adapted to 3 mm pixels and already used for the first two mRICH beam tests.
  - Maroc is not a universal long-term solution due to its poor timing
- A new front end with good timing, initially based on TARGETX used in Belle II, is being been developed by U. Hawaii.
- Due to limited availability of TARGETX chips, the front end will switch to the new SiREAD chip. This can be used for all EIC PID detectors and sensors.

Next Generation Photosensor Readout

- Building upon lessons learned from the development of photosensor readout for the Belle II upgrade (picosecond timing, low-cost, large muon system) and CTA SCT cameras ($1.40/channel)

- ASIC development important, but firmware and support have been the most critical issues

- UH has partnered with Nalu Scientific team to develop commercial variants (with functional extensions), to provide engineering support

- UH can then focus on strengths of an academic institution for innovation, testing and data analysis

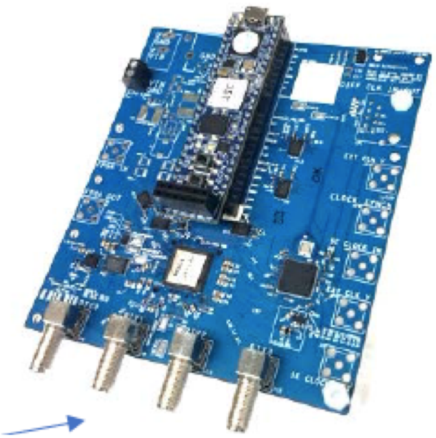
Univ. of HAWAI'I SiPiX LAB

Nalu Scientific
Data Acquisition Systems

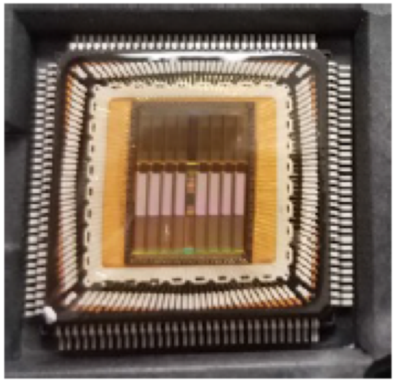
Current Nalu's SoC-ASIC Projects

Nalu Scientific
Data Acquisition Systems

Project	Sampling Frequency (GHz)	Input BW (GHz)	Buffer Length (Samples)	Number of Channels	Timing Resolution (ps)	Available Date
ASoC	3-5	0.8	32k	8	35	Rev 2 avail
SiREAD	1-3	0.6	4k	64	80-120	Rev 1 avail
AARDVARC	6-10	2.5	32k	4-8	4-8	Rev 2 avail
AODS	1-2	1	8k	1-4	100-200	Nov 2019



- **ASoC**: Analog to digital converter System-on-Chip
  - Rev 1 under test – **Funded Phase II - Eval card available**
- **SiREAD**: SiPM specialized readout chip with bias and control
  - Rev 1 under test
- **AARDVARC**: Variable rate readout chip for fast timing and low deadtime
  - Rev 1 under test – **Funded Phase II**



All chips, are designed with commercial grade tools and licenses and can be sold once commercialized.

SiREAD Electronics Evaluation

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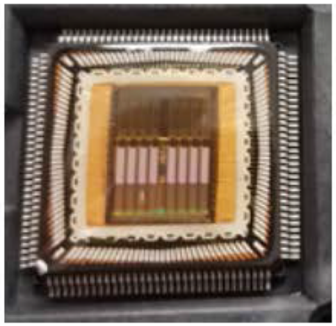
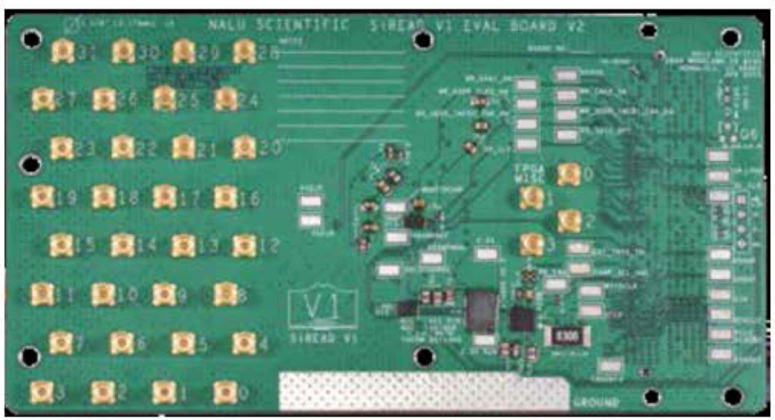
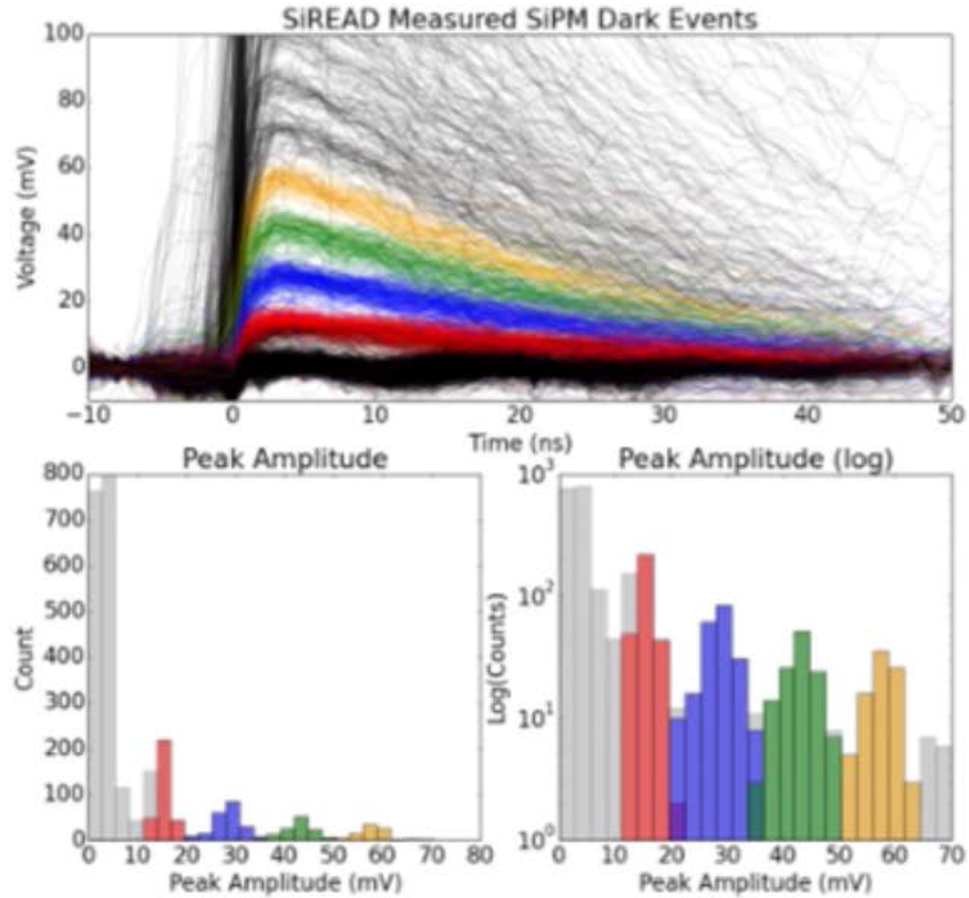
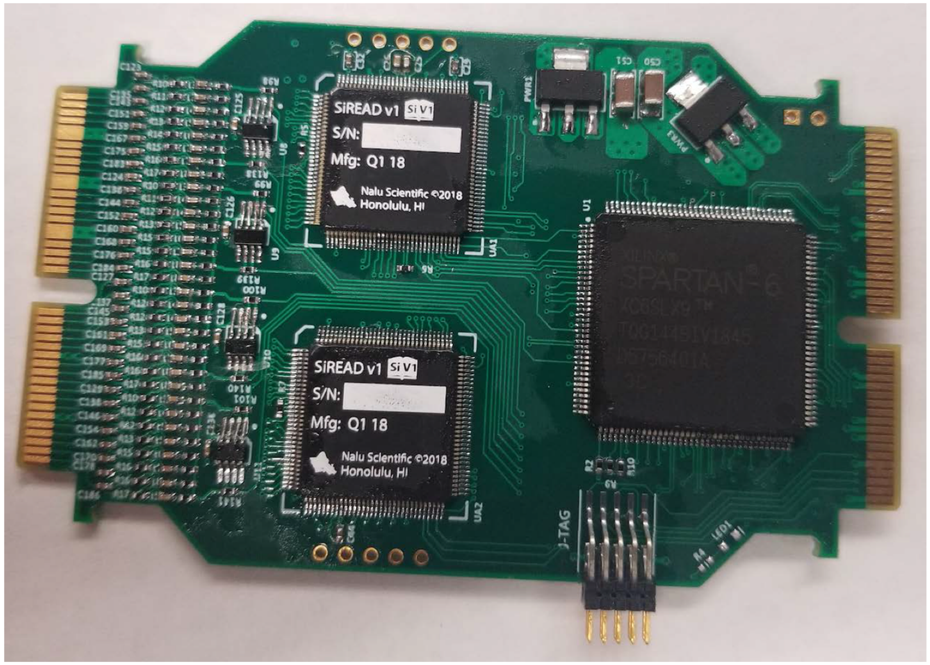






Micrograph of the fabricated prototype SiREAD (**top left**). Prototype SiREAD on the evaluation PCB (**top middle**). Superimposed dark count waveforms recorded from a SiPM using the SiREAD operating at 1 Gsa/s (**right**). High channel count evaluation PCB for SiREAD with 32 dedicated MMCX connectors (**bottom left)**.

MaPMT Readout



Photograph of the 64 channel SiREAD based (2x SiREAD rev.1) readout card as a building block for the 256 MA-PMT readout.

Photograph of the first generation of 256-anode 2" PMT readout for use with mRICH prototype in the Fermilab beam test facility.

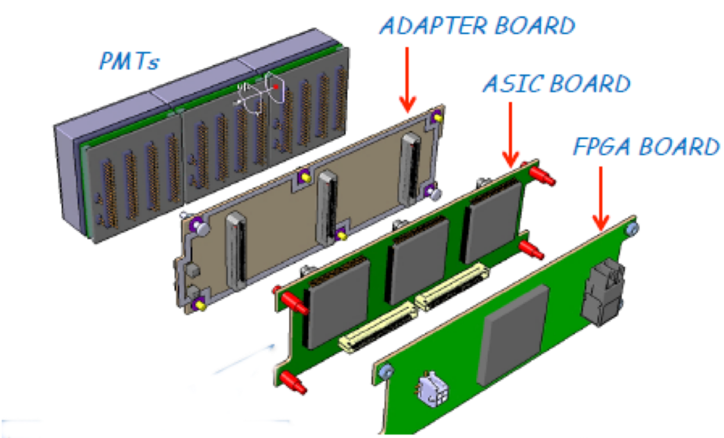
Nalu Scientific
Data Acquisition Systems

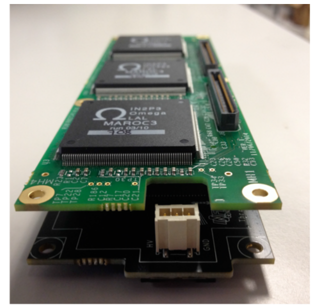
HW/FW Development

- Need for robust firmware development
- Nalu Scientific team provides in-house FW development, with institutional memory
- UH provides comprehensive bench, environment and picosecond laser/photosensor testing
- UH hiring new EE post doc on July 3rd (pending hiring paperwork)
- Immediate push is to get SiREAD version of 256 anode PMT readout working; evaluate performance; design more compact version

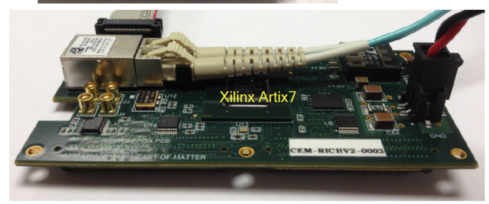
Electronics – Maroc (used for FY17-18 mRICH beam tests)

CLAS12 RICH electronics





Adapter & Asics Boards



FPGA Board

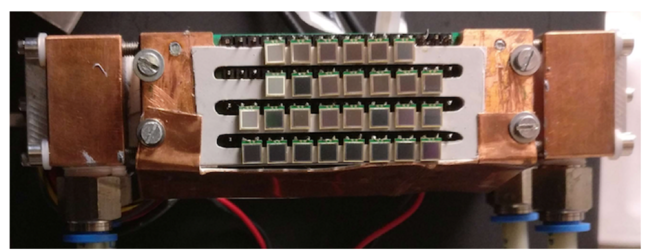
SSP Fiber-Optic DAQ

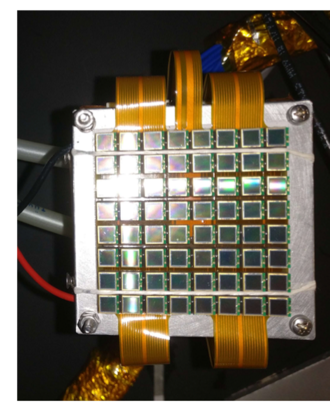
SiPMs

- ✓ Mass production technology
- ✓ Photon counting
- ✓ Excellent time resolution
- ✓ Compatible with magnetic field

- ✓ High dark rate
- ✓ Low radiation tolerance

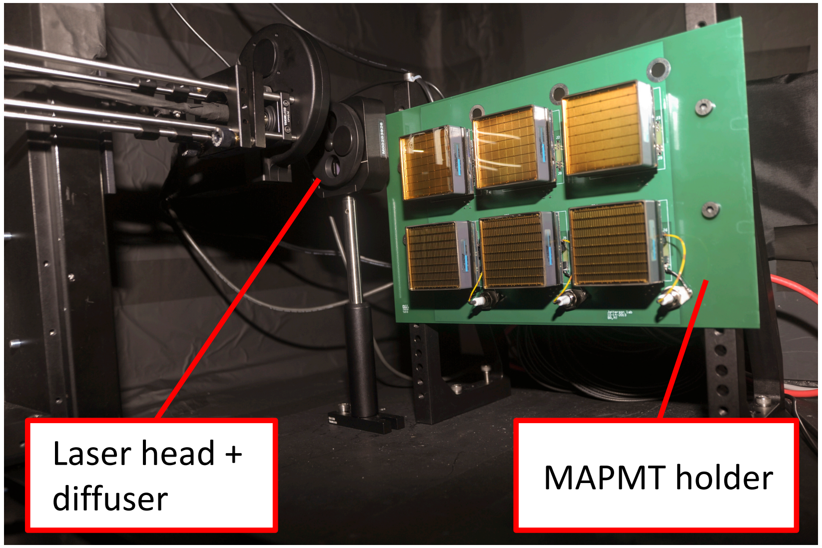
} Work at low temperature





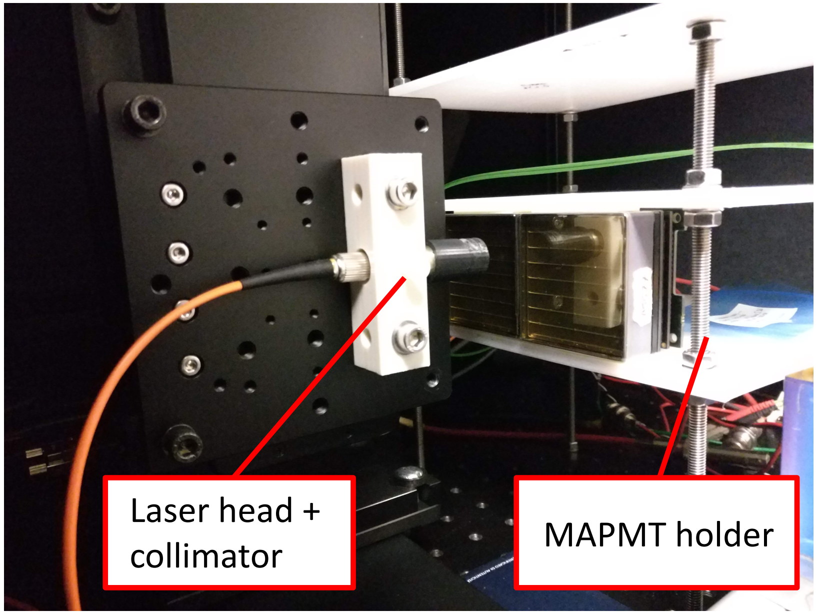
Pulsed Laser Test Benches

Detailed characterization
Sensors: gain, efficiency, cross-talk, radiation tolerance
Electronics: gain, cross-talk, thresholds, time resolution



JLab

632 nm picosecond pulsed laser light
Light diffuser to illuminate the whole MAPMT surface
Standardized system with CLAS12 electronics
H8500 6x6 mm^2 pixel sensor so far

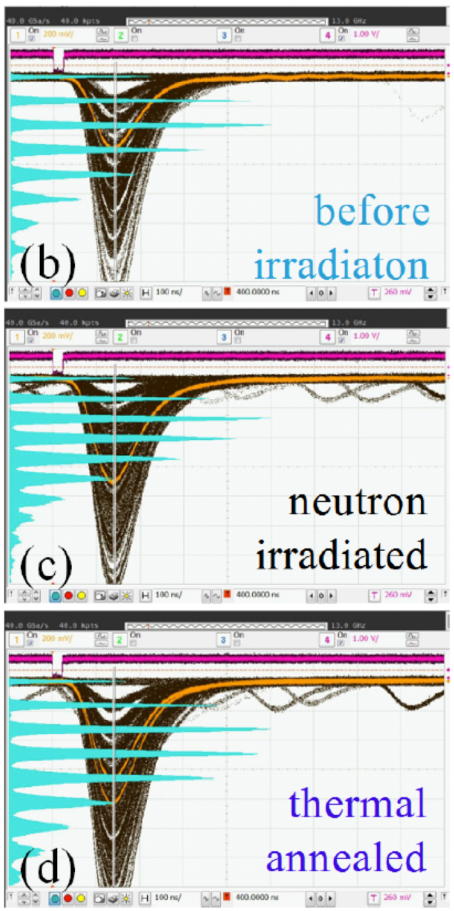


INFN

632 nm and 407 nm picosecond pulsed laser light
Light concentrator to scan the pensor surface
Flexible layout supporting various sensors and
Front-End electronics

SiPM Radiation Tolerance

T. Tsang et al.
JINST 11 (2016) P12002

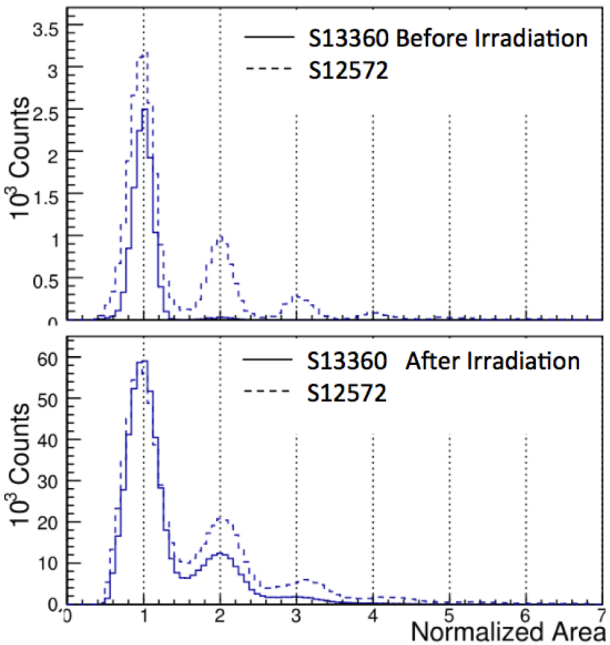


T= 84 K
10^9 n_{eq} cm^2
Annealing at 250 °C

I. Balossino et al.
NIMA 876 (2017) 89

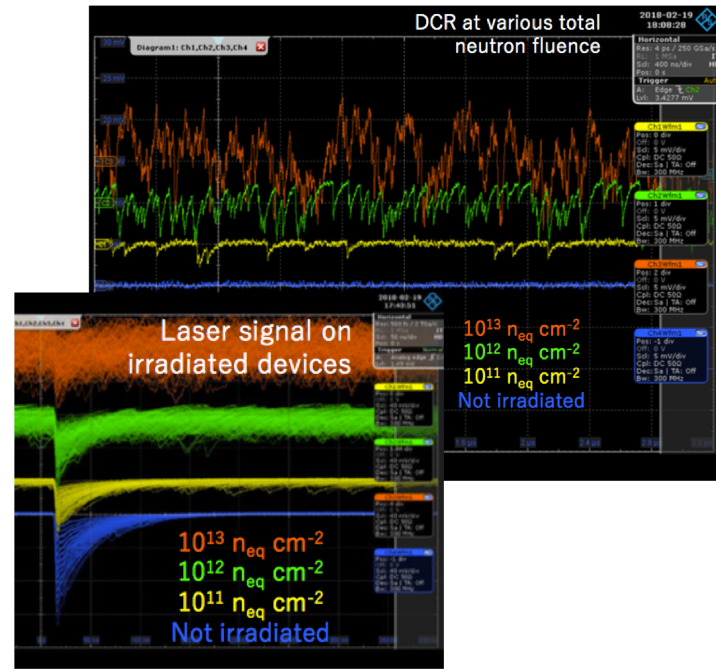
Single-photon capability after irradiation ?

S12572 standard technology
S13360 trench technology



T= 0 C
few 10^9 n_{eq} cm^2

Paolo Carniti
@ RICH 2018



SiPM: Hamamatsu S13360-1350CS (50 μm cells)

Temperature: –30 °C

Bias: V_{BR} + 1.5 V

Electronics Status and Plans

F19 Progress:

- First generation firmware for front-end to back-end communication
- Development of pulsed laser test benches for detailed characterization
- Radiation tolerance study for SiPM

FY 20 proposed activity:

- Integration of the SSP DAQ protocol with the SiREAD front-end chips
- Readout adaptation for the dRICH prototype
- Development of a portable DAQ system derived from the CLAS12 RICH readout
- Study SiPM single-photon detection performance in the EIC environment in collaboration with other eRD Consortia and experiments

eRD14 FY19 budget request (including overhead)

5.9 Budget by project

	100%	80%	60%
dRICH	52,000	35,000	20,000
mRICH	78,300	63,800	49,500
DIRC	134,000	108,000	82,000
high-B	39,300	32,100	32,100
LAPPD	120,000	100,000	75,000
Electronics	92,000	75,000	56,000
Total	*515,600*	*413,900*	*314,600*

5.10 Budget by institution

	requested	approved	fraction
ANL	120,000	100,000	75,000
CUA + GSI	134,000	108,000	50,000
GSU	68,300	53,800	39,500
INFN	94,000	72,000	50,000
JLab	9,700	9,700	9,700
U. Hawaii	60,000	48,000	36,000
U. SC	29,600	22,400	22,400
Total	*515,600*	*413,900*	*314,600*

- Please note that the rollover funds from FY19 are small.

Thank you!

More information on EIC PID activities can be found at the recent workshop

https://indico.bnl.gov/event/6351/

EIC PID workshop

Jul 9, 2019, 8:00 AM → Jul 10, 2019, 5:00 PM US/Eastern

https://bluejeans.com/315979113 (Stony Brook)

Description Workshop on current R&D activities for particle-identification for Electron Ion Collider.

We aim to bring together experts from various groups of the EIC community that have been actively engaged in the development of PID instrumentation for EIC in order to establish direct communication channels between the groups, identify potential needs for joint R&Ds, and explore opportunities for collaborative efforts.

dRICH IRT - Detailed analysis on L1

$$L_1(p,t,r;h) \equiv G(\theta_h^{t,r}|\theta^{c,r},\sigma_{\theta^{c,r}})\cdot P_S(N_a^{c,r}+1;N^{c,r})$$

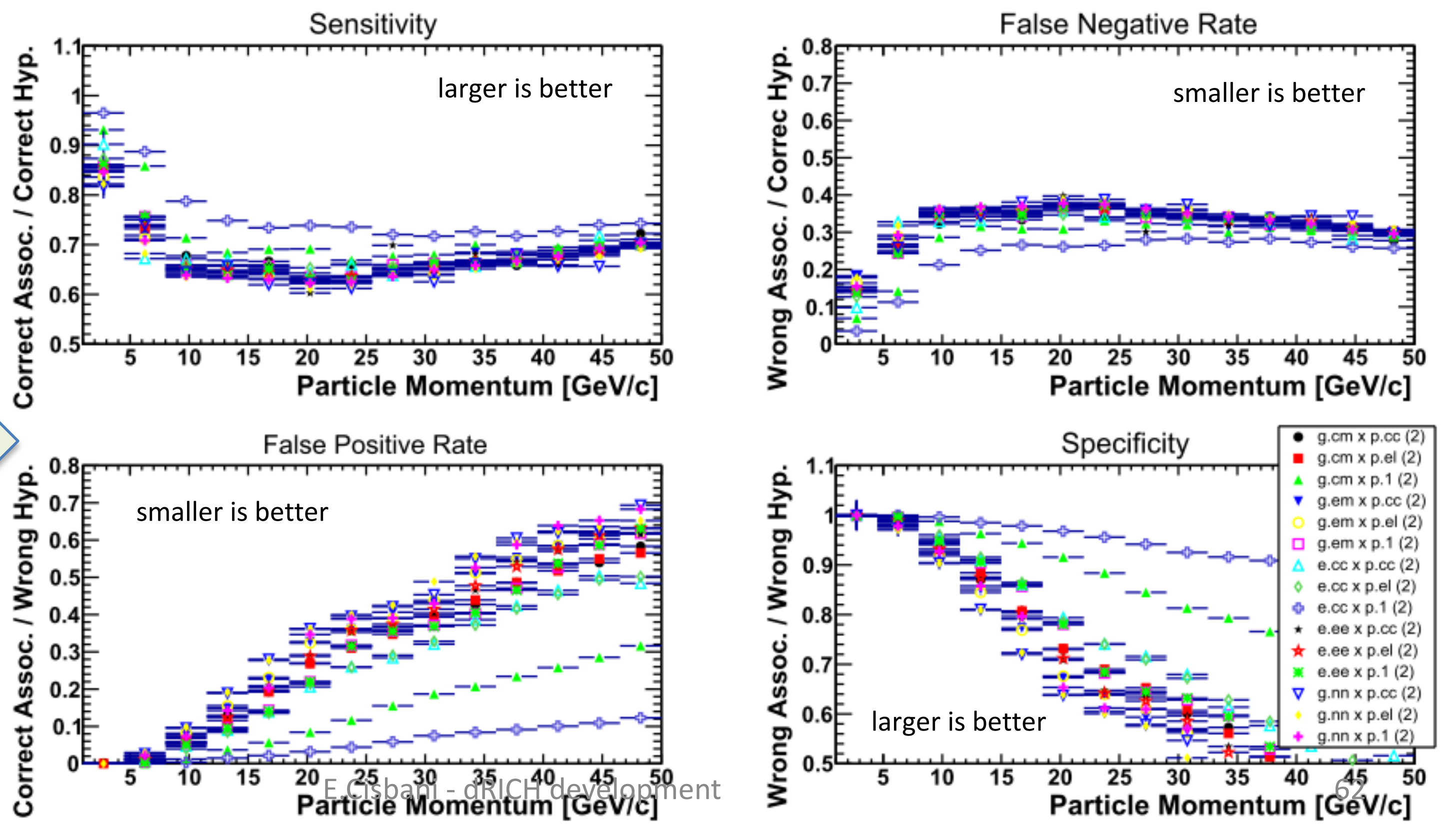
Degree of correlation of estimated and expected angle

Probability to assign a new photon to the track/rad/part by random choice

- Gaussian distribution with max=1
- Normalized gaussian (integral = 1)
- $\boxed{\text{ERF function}}$
- =1 (no contribution)
- Combine correlation and anti-correlation

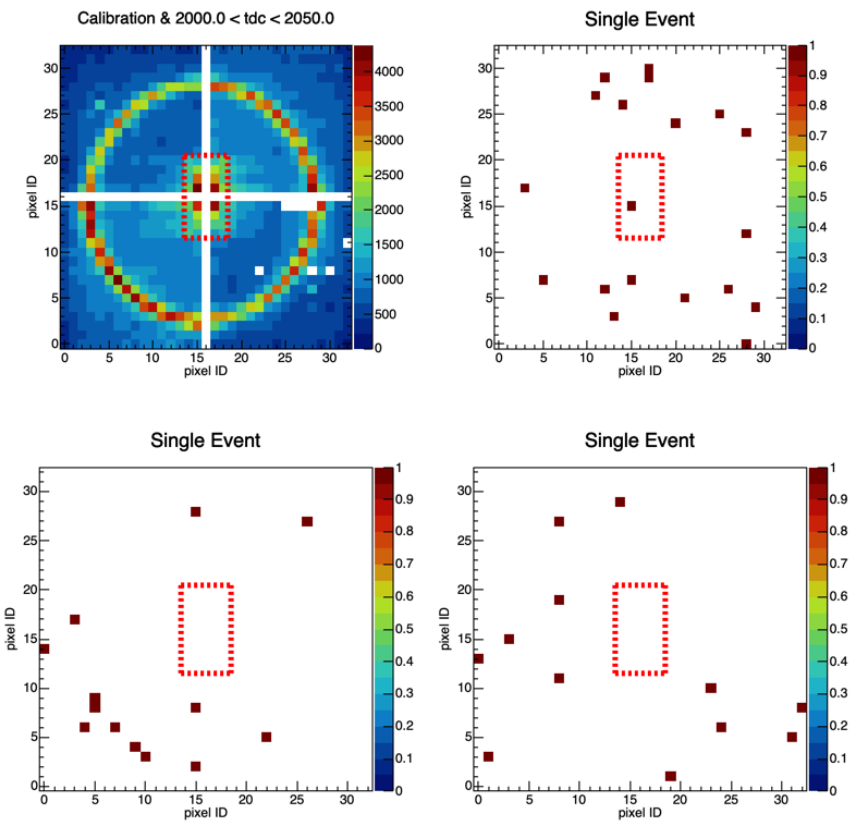
- Cumulated Poisson: prob. assign one or more photon to a given track/rad...)
- Partitioning: enumerate all combinations on "n" photons into "m" partitions (track/rad..);
- $\boxed{\text{=1 (no contribution)}}$

L1=(1-ERF) provides best predictions

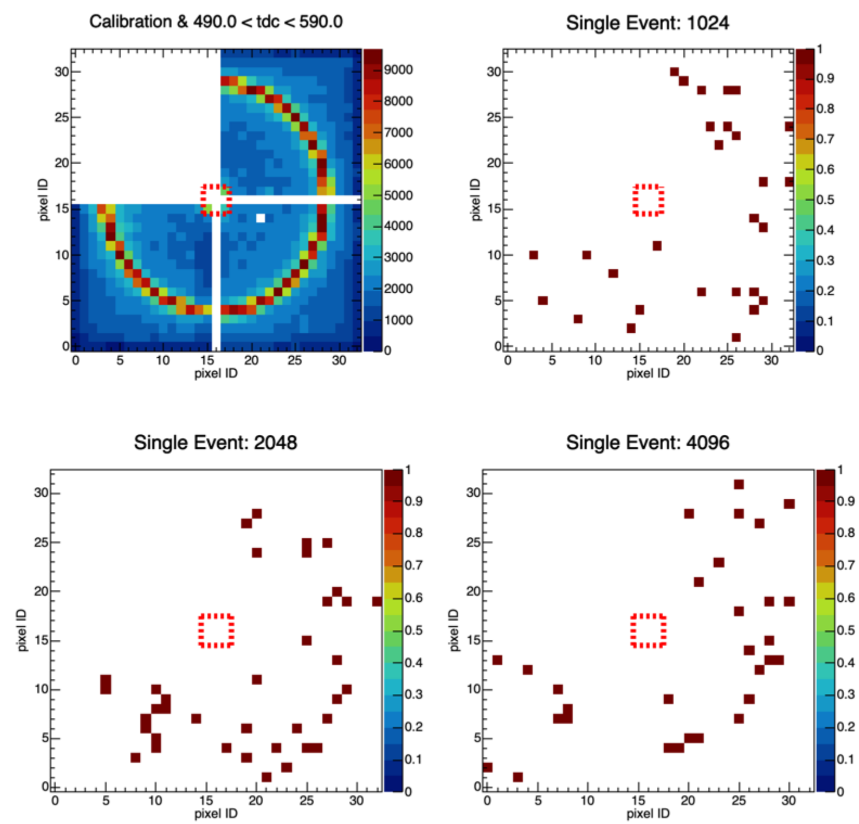


Event-by-Event Analysis (example)

With 4 H13700 PMT's



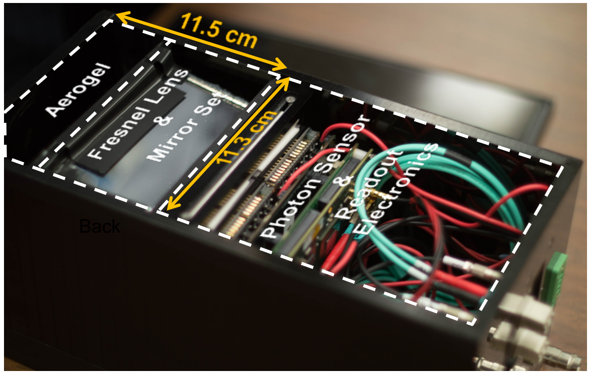
With 3 Hamamatsu SiPM matrices (-30^{0}C)



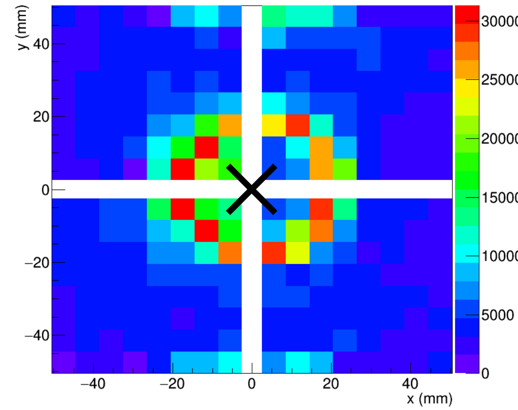
120 GeV/c proton beam incident at the center of mRICH - baseline analysis

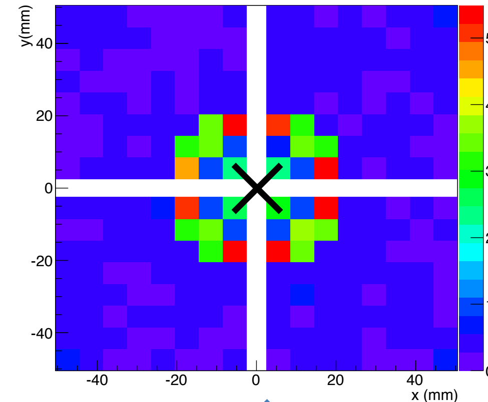
1st and 2nd Beam Test Comparison (120 GeV Proton Beam)

The 1st test beam result verified mRICH working principle and validated simulation



1st mRICH prototype was tested at Fermilab Test Beam Facility in April 2016

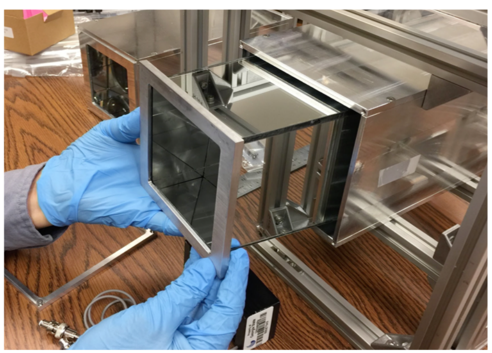




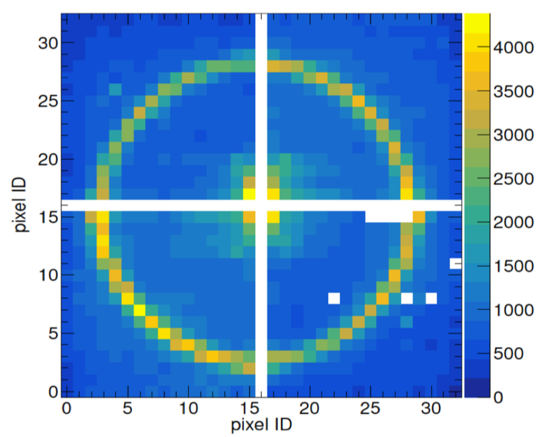
Images from 120 GeV Proton beam

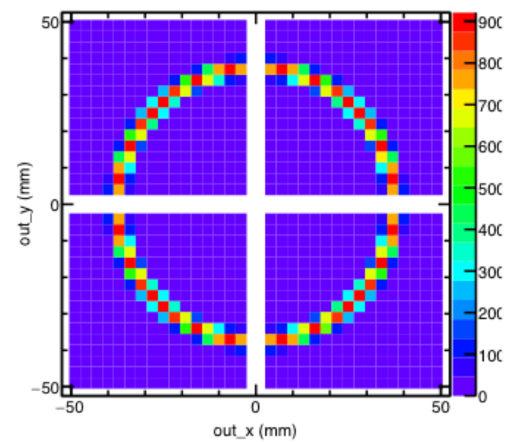
Simulated Images Using GEANT4

New features: a) separation of optical and electronic components; b) longer focal length (6”); c) 3mm x 3mm photosensors.



2nd mRICH prototype was tested at Fermilab Test Beam Facility in June/July 2018

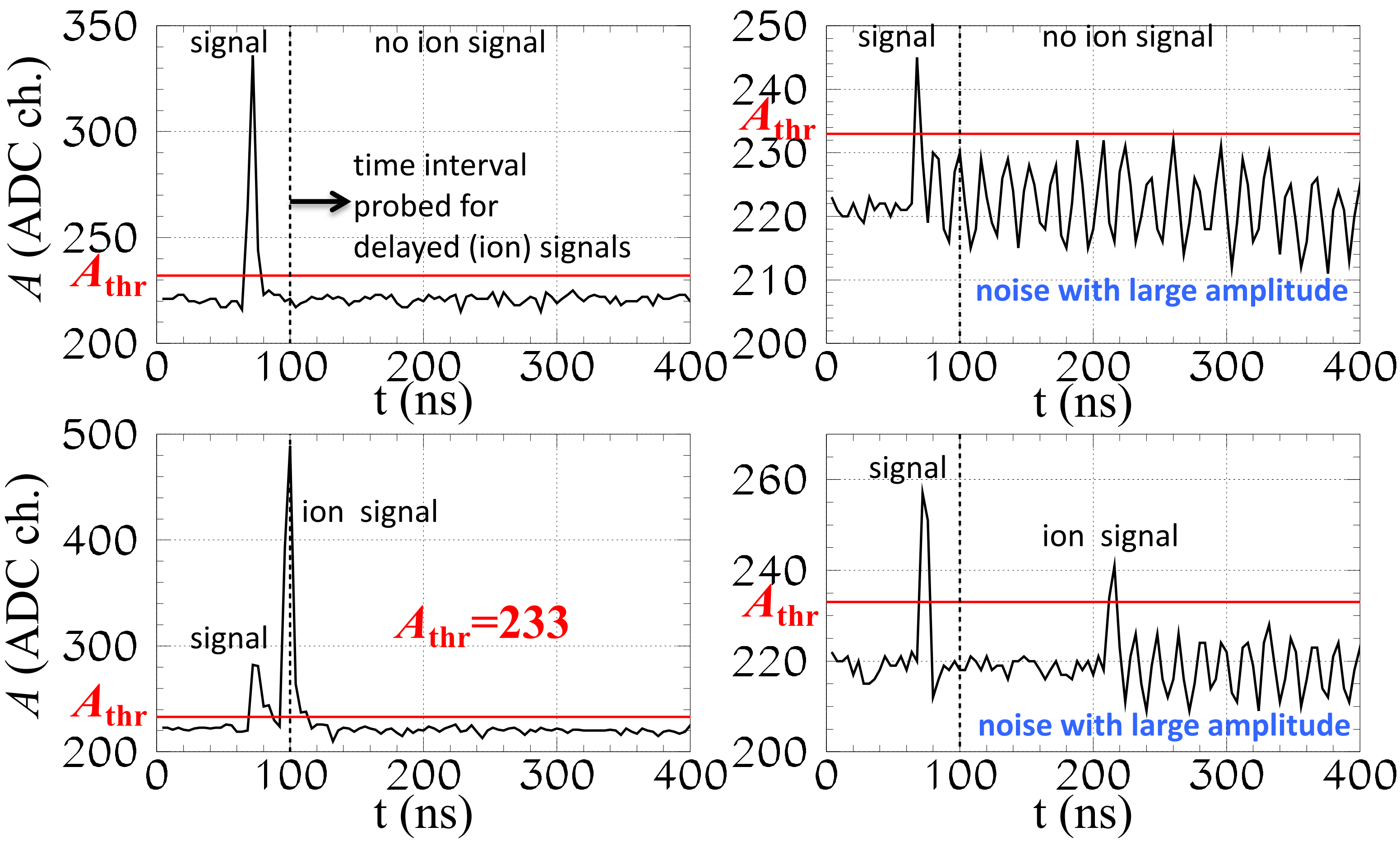




High-B results from FY19 Ion-Feedback Studies

10-µm Planacon: Ion Feedback

The accuracy of the extracted ion-feedback rate strongly depends on the **noise** of the signal line. The value of the **threshold amplitude defining a signal, A_{thr},** critically affects the estimate of ion feedback rate.



$N_{signals}$:

$A_{\max} \geq A_{thr}$

$t < 24$ ns

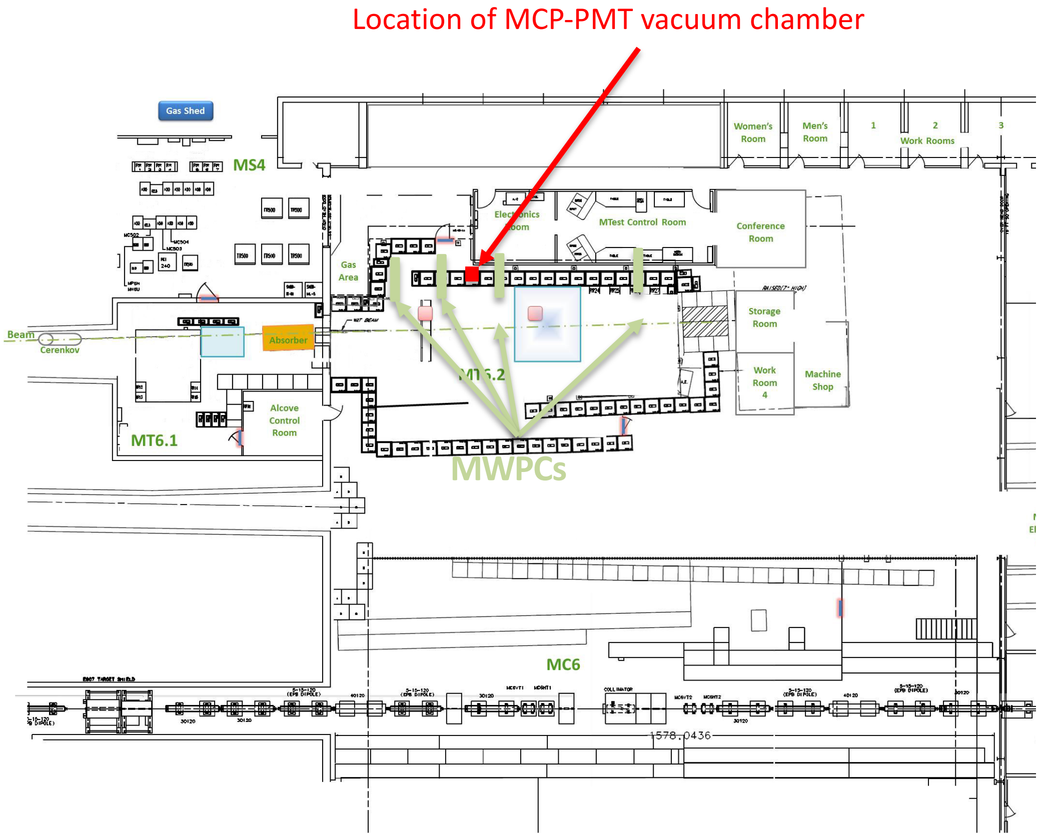
N_{ions} :

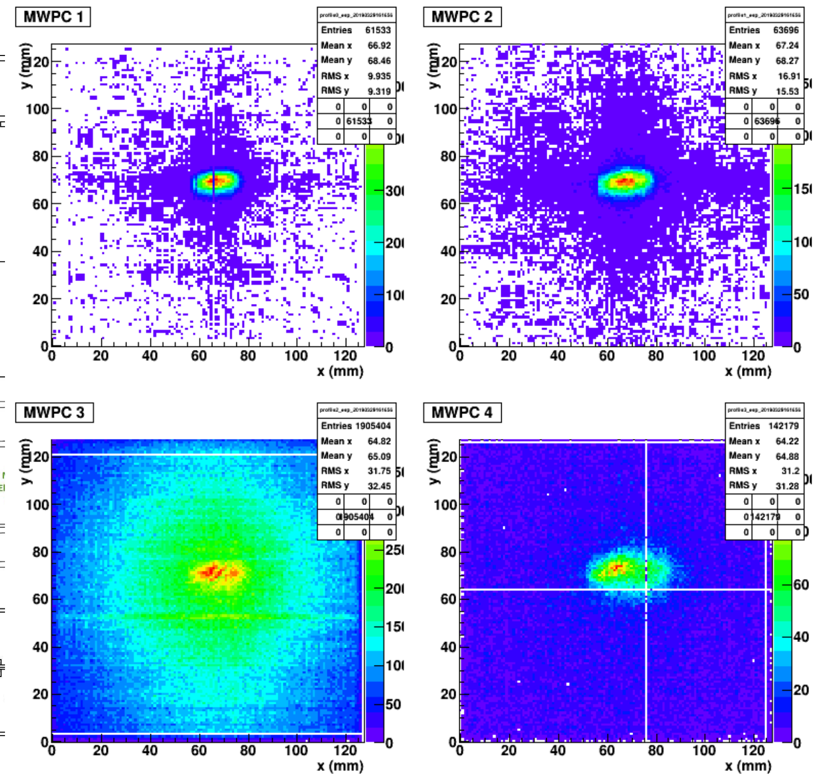
$A_{\max} \geq A_{thr}$

$t > 100$ ns)

$$Rate = \frac{N_{ions}}{N_{signals}}$$

Tracking system





- 4 MWPC's for tracking, MWPC 1 and 2 upstream, and 3 and 4 downstream
- In MWPC 3 we got a lot of spray from hadronic interactions in the vacuum chamber